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The Value of Carbon Sequestration in the Developing World: Making the Economic Case for Tree Planting in Laos

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THE VALUE OF CARBON SEQUESTRATION IN THE DEVELOPING WORLD: MAKING THE ECONOMIC CASE FOR TREE PLANTING IN LAOS

By

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List of abbreviations

BOL	Bank of Lao PDR
CBA	Cost-benefit analysis
CO_2	Carbon dioxide
CVM	Contingent valuation method
EPA	Environmental Project Agency of the United States
GDP	Gross domestic product
GHG	Greenhouse gases
GIS	Geographic information system
ha	Hectare
IAM	Integrated assessment model
IPCC	The Intergovernmental Panel on Climate Change
IRR	Internal rate of return
IWG	Interagency Working Group on Social Cost of Greenhouse Gases of the United States
LAK	Lao kip currency
Lao PDR	Lao's People Democratic Republic
LEV	Land expectation value
NFV	Net future value
NPV	Net present value
NSEDP	National Socio-economic Development Plan
SCC	Social cost of carbon
SDR	Social discount rate
SRR	Social rate of return
SRTP	Social rate of time preference
tCO_2	ton of carbon dioxide
TEV	Total economic value
WTP	Willingness to pay

Abstract

Tree plantations in developing countries are mostly driven by private sectors, mainly to increase forest cover and meet the timber demand. However, research studies on tree plantations in Laos, for instance, show that despite high profitability tree farmers and private companies face many challenges such as low timber quality, low timber selling price and slow plantation expansion. These challenges could be the result of slow policy improvement processes or the lack of basis on the justification of government intervention. This study uses a policy decision tool - a cost-benefit analysis to evaluate social costs and social benefits from private tree plantations by considering the market and non-market values. Among various non-market values from tree plantations, carbon sequestration is selected. The goal of this study is to demonstrate how the value of non-market benefits can shape environmental policy in developing countries. Given data limitations, the study was conducted based on the best existing data possible, using a combination of qualitative and quantitative analysis. The benefits of carbon sequestration in monetary value are obtained. A dual-discounting approach was applied to discount future net benefits of market and non-market components to arrive at a present value. The result of the study can be used as a basis to accelerate government intervention for private tree plantation investments. It was found that the benefit value of carbon sequestration in 2020 dollars was estimated to be $472.8 million over 30 years of tree plantation. This value can translate into the budget for government intervention to improve current tree plantation practices and regulations, increasing profitability for tree growers and eventually increasing tree planting in Laos. Further research to improve the results of this study is also discussed.

1 Introduction

Although it is well known that trees provide natural sequestration that helps to remove carbon dioxide from the atmosphere, it is unfortunate that this benefit to society is not taken into account in the evaluation of private investment. An example of tree plantation investments in Laos, or an official name - Lao's People Democratic Republic (Lao PDR), shows that profits are the only indicator to decide whether the investment is economically efficient or not; economic efficiency means that total benefits are greater than total costs, which in turn means that net benefits are positive. An optimally efficient program has the highest net benefits. However, there are other benefits such as water resource protection, soil erosion protection, carbon sequestration, and other ecosystem services stemming from tree plantations, and this should affect the decision of private investors to plant more trees.

Settings and unique characteristics of Lao PDR provide a suitable justification for this research study to take place. First, tree plantations are part of rural livelihoods where people plant trees to contribute to their financial security (Newby et al., 2014). Second, tree farmers face challenges; in particular, their selling prices are lower compared to other countries in the same region (Maraseni et al., 2018). Last but not least, to date, there is no study to explore the benefits to society stemming from tree plantations in Lao PDR, and how accounting for these missing benefits can justify the need for government intervention. This study aims to illustrate how the integration of social benefits can promote tree plantation investments in the country. Before we go into detail about the study, it is essential to be informed about the global concerns of carbon dioxide emissions.

Carbon dioxide is one of the six greenhouse gases (GHG), and certainly the one causing the most global climate modification. The 2018 IPCC Special Report on Global Warming of 1.5°C (SR15) reports that we are now in the era of climate change, warmer temperature, sea-level rise, shrinking Arctic ice, change of crop yields, and increased prevalence of the disease. Damage due to GHG emissions is unprecedented and affects all economic sectors across wide spectrums (Hoegh-Guldberg et al., 2018). The Stern Review (2007) has estimated that at least 5% of the global GDP each year will be lost due to damage caused by climate change. With a range of risk and uncertainty taken into account, it can go up to 20%. Further, the damage is expected to increase over hundreds of years from now, affecting several future generations to come. This requires aggressive actions with strong collaborations around the globe, including all countries without regard to economic size.

Many small countries are climate-vulnerable, although their emission share is very minimal compared with the global GHG emissions. It is reported that 70% of the global GHG emissions in 2016 are accounted for by the top ten emitters, including China, the U.S., and India (Ge & Friedrich, 2020). Most GHG emissions are from energy consumption in countries with large economic size, and the emissions in some countries have been decreasing while in others have been increasing (British Petroleum, 2019). Nevertheless, the small emitting countries shall also aim to maintain or reduce their emissions, ensuring their development toward the green economy. It is also a shared responsibility where each country takes its action locally for the global benefits. Thus, it requires a sound policy to involve all sectors to combat climate change together.

In the case of Lao PDR, a study was done to estimate the impacts of climate change using a computable general equilibrium model. The results show that the impact on crop yields and commodity prices would decrease gross domestic product by 2.8%, which is equivalent to $80 million in 2050 with the base year of 2004 (Kyophilavong & Takamatsu, 2011). There are also other damage categories, such as floods, droughts, and diseases. This is partly because the global emissions are increasing, and partly because the forest watershed system is being destroyed due to land-use change and logging.

To recover the destroyed forest cover, the Lao Government allocated an area for tree plantations of 500,000 hectares (ha) in 2005 and an additional 700,000 ha in 2018, resulting in the plantation target of 1.2 million ha to be completed by 2030. Figure 1.1 shows forest cover from 1940 to 2015 with forest cover target in 2020. The plantation target is a means to promote commercial tree plantations, aiming to increase forest cover as well as wood production.

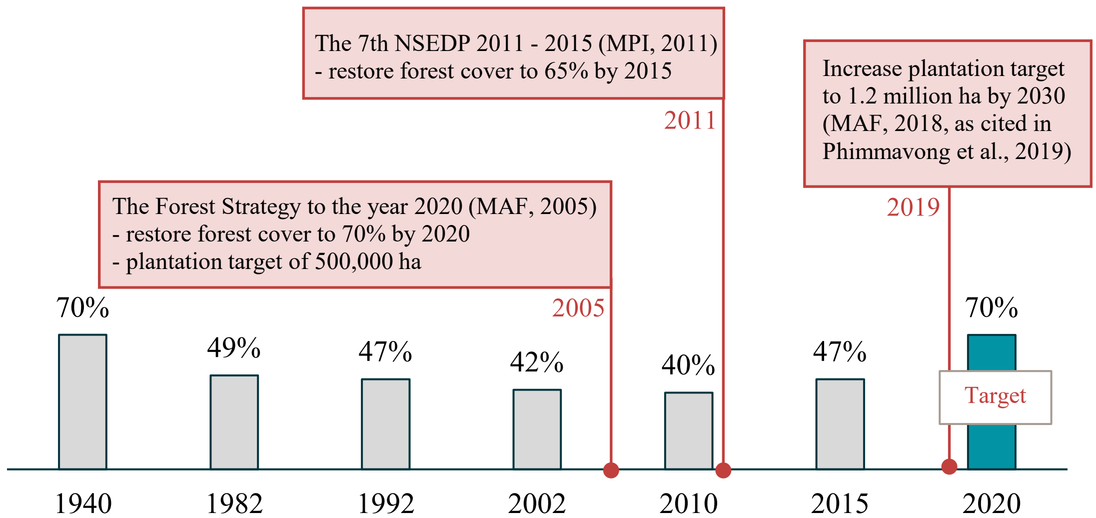

Figure 1.1 Forest cover (%) and government policies from 1940 – 2020 (Ministry of Agriculture and Forestry [MAF], 2005; Ministry of Planning and Investment [MPI], 2011; Phimmavong et al., 2019)

Nevertheless, the tree farmers in Lao PDR face many challenges, including low timber quality, low timber prices, high costs of plantations and transportation, and official and unofficial charges (Maraseni et al., 2018). Also, private companies have encountered resistance for plantation expansions among local communities (Phimmavong et al., 2019). Trees are also cut earlier than their optimal age, due to the impatience of owners who plant trees as part of their rural livelihoods. This implies that wood production is not maximized. The recent studies on financial returns for two tree species in Lao PDR, teak and eucalyptus, show high financial returns from timber selling compared to costs of plantations in present value terms (Maraseni et al., 2018; Phimmavong et al., 2019). This suggests that the plantation investments are profitable. However, the plantation expansion has been slowed, and wood production to meet the future demand is also uncertain. This indicates that the tree market is not operating efficiently. Solutions such as a collaborative investment model and a co-innovation mechanism are proposed (Maraseni et al., 2018; Phimmavong et al., 2019). Therefore, it is the motivation of this research study to further look for ways to accelerate the economic need for government intervention.

This research study uses the decision tool in policymaking called cost-benefit analysis (CBA) together with the first equimarginal principle and the Pigouvian subsidy rule. This aims to integrate additional benefits, such as social and environmental benefits and costs, into a more fully comprehensive financial analysis. While financial analysis shows the profitability of an investment, the CBA tool takes social welfare into consideration: trees provide net benefits to people. This CBA tool is used to promote sound policy by incorporating all costs and benefits, including financial and non-financial components, into the decision-making process. The first equirmarginal principle of economics and the Pigouvian subsidy rule are applied to identify the magnitude and rationale of government intervention in private investment. This research is unique to Lao PDR in that it internalizes social benefits into the decision-making process for the private investment. There are very few studies of this type anywhere in developing countries in Southeast Asia.

The central aspect of CBA is that the result is in monetary terms, which is to say that the human-use services provided by trees can be estimated in money. In tree plantations, there are two types of values; market and non-market values. Financial costs are market values, which can be easy to quantify using data from well-established markets. However, non-market values, such as benefits of soil erosion control, clean air, support of biodiversity, recreation, and carbon sequestration, are not currently tradable in a well-established market and require alternate methods to monetize. Non-market values in this study are based on conservative assumptions by only considering the main benefit, which is carbon sequestration. Also, while carbon sequestration provides global benefits; in this study the value of carbon sequestration is based on benefits provided to local and regional populations only, because per CBA the scope of a study should be attributed to a specific jurisdiction so that a policy can be made from the CBA result with roles of all concerned actors within the same jurisdiction are being determined.

Another challenge is how to address the timing of costs and benefits. Costs of investment occur mostly in the present time, while benefits mostly occur in the future, often far into the future by decades or even centuries. Due to social preference for benefits now versus the future, inflation, and the risk associated with uncertainty, the values occurring at different times need to be adjusted per standard practices in CBA. Therefore, all values can be compared on a present value basis. Furthermore, the magnitude of discounting the future can also represent equity across generations for a long-term investment, such as 100 years or more. The technical efficiency estimation is not the only consideration that makes a sound environmental policy but also the equity value-judgment angle. This study utilizes different literature to assign a social discount rate to monetize streams of future benefits, from the mathematical estimation of Ramsey (1928) to the Stern Review (2007) based on value judgment in the monetization of benefits for future descendants. Conservative discounting is used in this study to ensure that the results are defensible.

The study also acknowledges possible drawbacks. Given that primary data are unavailable, data are mainly obtained from existing literature. Thus, the accuracy highly depends on the quality of data from previous studies. It is important to interpret the results with caution. Nevertheless, the results of this study can be summarized into two key takeaways.

1. The benefits of carbon sequestration, which accrue to society, can be used as the basis to justify the additional intervention aiming at the improvement of the market efficiency for the private investment; and
2. Social preference and value judgment can influence the study results by either increasing or decreasing the social benefits, in return, affecting how much government intervention should be.

Nonetheless, manipulating the technical elements of this study always results in a consistent outcome, which is that carbon sequestration yields positive net benefits to society under all scenarios. There is no exception to this finding.

The manuscript has five (5) chapters, including this chapter. Chapter 2 summarizes previous studies on applications of cost-benefit analysis (CBA) for tree plantations as well as other CBA-related components such as market interest rates, discounting approaches, the social discount rate, and the social cost of carbon. Chapter 3 describes the study design to provide a context for CBA for tree plantation investment. Chapter 4 includes results and discussion of the specific CBA, given the best and most appropriate analytical analysis, with sensitivity analysis for uncertainty in the input data. Finally, Chapter 5 concludes the research study with major conclusions highlighted and proposes possible research extensions following the completion of this study. The technical details, together with statistical analysis and formulas, are included in the Appendix.

2 Literature review

Any investment requires an evaluation to compare different options and to make the optimal decision based on specific criteria. For public investment, maximizing social welfare is the primary goal, ensuring economic efficiency along with the equitable allocation of resources. However, when it comes to sustainability, where future generations are affected but cannot explicitly represent themselves in today's decisions, efficiency is not a sufficient criterion (Tietenberg & Lewis, 2018, p. 478). This section provides a review of cost-benefit analysis and its application specifically to the plantation sector. The distinctions of financial returns and economic benefits, characterizations of the economic benefits, as well as values of greenhouse gas emissions avoided in monetary terms, are also examined and incorporated. The selection of the social discount rate is summarized from prominent literature; there is some controversy and a healthy debate in the literature in selecting the appropriate rate of time preference for a developing nation such as Lao PDR. This section provides readers with the foundation of economics and its link to developing good environmental policy for all parties (as opposed to a study only of private investment that affects few). Dollar values otherwise specified, both estimated in this study and cited from other studies, are reported in the year 2020.

2.1 Investment evaluation tool

Cost-benefit analysis (CBA) is a tool to find out whether the benefits of a project investment are higher than its costs in present value terms. Public investment often uses CBA to quantify all benefits and costs from both market and non-market values in monetary terms. Market values represent explicit cash flow such as costs and incomes; non-market values, while possibly substantive, cannot be determined in a traditional and well-established market. Non-market value is often implicit but vital to society, such as clean air and water, the natural filtration of wetlands and forests, and, to be sure, values associated with slowing and possibly reversing climate modification from carbon emissions.

In the private sector, financial analysis is mainly used to estimate financial returns on investment. This specifically includes only actual private costs and private benefits (or revenues) of an investment with no considerations of social costs and social benefits. In contrast, social costs and benefits are often the result of externalities, which are spillover effects affecting a third party, often society at large. For example, pollution from an industry affects the water quality of a downstream community. The integration of social values into financial analysis for the private sector is made possible with government intervention.

A comprehensive CBA requires including all market and non-market values that are estimable. These values can accrue at different times. To compare these values, it is necessary to convert them into present terms by discounting all future values and summing them together to arrive at the net present value (NPV). The main components of the conventional CBA include costs, benefits, interest rates, social discount rates, net present value, and a sensitivity analysis. An investment is efficient when its NPV is positive. However, negative NPV does not necessarily indicate a project should not be undertaken, particularly when an investment is to avoid catastrophe or risk to life, such as toxic pollutants, or when potentially large categories of benefits are excluded. Estimating the costs of the program using engineering data is typically easier to estimate than program benefits, especially if non-market categories are relevant.

Examples of some studies done for tree plantations in Asia region include Niskanen (1998) in Thailand, James & Francisco (2015) in Cambodia. Manivong & Cramb (2008), Maraseni et al. (2018), Phimmavong (2004), and Phimmavong et al. (2019) for private plantations in Lao PDR. However, a CBA of private investment in the region is limited at best and generally unavailable. It can be assumed that non-market values or social values external to private market transactions might be neglected or completely ignored from a benefit side for private investment.

Nevertheless, the results of the financial analysis of tree plantations in the region, which is not the same as CBA, show a positive net present value, even in the absence of non-market values. The integration of non-market values for the decision-making process is meaningful when dealing with a public investment. For example, a UK study by Kula & Evans (2011) shows that non-market values can help to justify the need for a public afforestation investment. This is made possible through the estimation of total economic value (TEV) which represents all values of environmental resources in monetary terms, including both market and non-market values. A detailed explanation is presented in the following section.

2.2 Characterization of costs and benefits of tree plantations

The first step in CBA is to characterize the costs and benefits of investment. There are three cost components. First, there are straightforward engineering expenses due to a project investment in addition to operation and management expenses. Second, there are opportunity costs, which are the foregone implicit benefits from another program that is not done because the program chosen yields higher net benefits. The opportunity costs are relevant when there are choices to be selected from, for instance, to either plant trees or to produce crops, but not both. Last, it is a cost due to adverse environmental impacts. Economists refer to this type of cost as negative externalities.

The benefits of investment, in environmental economics, refer to the total economic value (TEV). There are two main components in TEV of environmental resources which are active use value and passive use value (Cubbage et al., 2013). Active use value is comprised of direct use, indirect use and option value, while passive use value comprises existence value and bequest value. For an evaluation of project investment, direct use value is often included, because the benefit of direct use value can be easily derived by people who get benefits from a natural resource, for instance, timber. Meanwhile, other types of economic values are vital but less tangible, such as the value of fresh air, and require a method to valuing them. An investment that enhances economic values, particularly lesser tangible economic values, creates positive externality. The following paragraph describes each component of economic values.

Direct-use values are benefits from the active use of an ecosystem. It is further distinguished into consumptive (or extractive, such as timber) and non-consumptive (or non-extractive, such as recreation activities). Indirect-use values are benefits from ecosystems without direct interaction, such as water purification and carbon sequestration. Indirect services are usually pathways to active use services and values. Option values are benefits derived from the option to directly or indirectly use resource services in the future. People may not want to use it today but still want to preserve their option to use it in the future. The last is passive use or non-use values, which are values society places on the existing ecosystem but do not use the resource. There are two types of non-use values: existence value and bequest value. Both represent different forms of altruism. Existence value occurs when society is not interested in human uses at all but feels satisfaction from just knowing that ecological health services exist for the benefit of nature (Krutilla, 1967).

Because passive values are not associated with any behavior and must be obtained as stated preferences, this value category – and particular the associated monetization – is the most controversial and subject to validity concerns (Carson et al., 2001).

In climate change, a loss of active use value of environmental resources alone can cause substantial economic damage disproportionately distributed in a global context. The Working Group II of the IPCC, who deal with climate impacts, adaptation, and vulnerability, released results of observed impacts in natural and human systems in the IPCC Special Report on Global Warming of 1.5°C. Further, climate change can result in a global impact with a greater magnitude far into the future resulting from today's GHG emissions. Therefore, regardless of the controversy of passive-use values, it is essential to try to include them, or at least acknowledge them, in the total economic value. This is dealt with in detail in section 2.4.

To define what should be included in the total economic value, we should understand how economic value is derived from ecosystem functions. de Groot (1992) defines ecosystem functions as 'The capacity of natural processes and components to provide goods and services that satisfy human needs, directly or indirectly.' The distinction between ecosystem functions and ecosystem goods and services is that ecosystem functions always exist, while ecosystem goods and services are only recognized when people get benefits. Costanza et al. (1997) further define that 'Ecosystem goods (such as food) and services (such as waste assimilation) represent the benefits human population derives, directly or indirectly, from ecosystem functions.' The authors also note that the term 'ecosystem services' is to refer to all benefits stemming from ecosystems, including goods.

Based on the widely-cited Millennium Ecosystem Assessment (2005), the ecosystem services that affect human well-being are classified into four primary categories, including provisioning, regulating, information (or cultural services), and habitat functions (or supporting services) (Reid et al., 2005). Table 2.1 summarizes categories of ecosystem services with associated components of plantation forests. This shows that provisioning and cultural services have direct use values while regulating and maintenance services, such as carbon sequestration, soil and water regulations, have indirect use values. All of these services may have non-use analogs.

Table 2.1 Categories of ecosystem services and associated components of total economic value

Ecosystem services		**Components of total economic value**				
Section	**Division**	**Use values**			**Passive-use values**	
		Direct use	**Indirect use**	**Option use**	**Existence**	**Bequest**
Provisioning	Nutrition	✓		✓		✓
	Materials	✓		✓		✓
	Energy	✓		✓		✓
Regulating and maintenance	Mediation of waste, toxins and other nuisances		✓	✓		✓
	Mediation of flows		✓	✓		✓
	Maintenance of physical, chemical and biological conditions		✓	✓		✓
Cultural	Physical and intellectual interactions with ecosystem	✓	✓	✓	✓	✓
	Spiritual, symbolic and other interactions with ecosystem	✓	✓	✓	✓	✓
Supporting	Habitat for resident plants and animals and migratory species		✓	✓		✓

Source: modified from Masiero et al. (2019) and de Groot & van der Meer (2010).

In the case of tree plantations, which are human-made forests for wood production, the ecosystem services provided from the investment are presumably lesser than that of natural forests. de Groot & van der Meer (2010) summarize the difference in the provision of goods and services between natural forests and plantations, as shown in Table 2.2. It can be seen that some goods and services such as food, fodder and fertilizer and natural hazard regulation provided by plantations remain the same as natural forests, while other services are mostly reduced. The limited ecosystem services from tree plantations can also be explained by monocultural practices (only selected species being planted), in which biodiversity is completely lost.

Table 2.2 The provision of goods and services of natural forests and plantations

Main categories	**Goods and services provided by forests**	**Natural forests**	**Tree plantations**
Provisioning	Food	✓	0
	Raw materials	✓	+
	Energy resources	✓	+
	Fodder and fertilizer	✓	0
	Genetic resources	✓	-
	Natural medicines and pharmaceuticals	✓	-
	Biochemicals (non-medicinal)	✓	-
	Ornamental resources	✓	-
Regulating	Air quality regulation	✓	-
	Climate regulation	✓	-
	Water quality regulation	✓	-
	Water regulation	✓	-
	Natural hazard regulation	✓	0
	Erosion prevention	✓	-
	Maintenance and restoration or productive soil	✓	-
	Biological control	✓	-
	Pollination	✓	-
Cultural	Aesthetic information	✓	-
	Recreation and nature-based tourism	✓	-
	Cultural heritage and identity	✓	-
	Inspiration	✓	-
	Spiritual and religious information	✓	-
	Educational information	✓	--
	Science	✓	--
Supporting	Refugium	✓	---
	Nursery	✓	?

+/0/– indicates a difference in services-provision between natural and plantation forest ("+" means service is enhanced, "0" means remains the same, "-", "- - ", "- - - " means service is reduced in a progressively greater magnitude, and "?" means unknown).

In a simple classification, the total economic value can be categorized into two types based on whether it can be readily bought and sold in a market or not. The two types of values are market and non-market values. Market values are tradable values for which data on prices are readily obtained. Goods and services under the provisioning service category are mainly market values such as food, raw materials, and energy resources. For tree plantations, the major economic value is derived from timber harvesting, which is an example of market value and can be estimated by the financial analysis for tree plantations using the costs of plantations and incomes from selling timber.

In contrast, non-market values are values people place on natural resources and environment that cannot be purchased in a well-established market. Many studies monetize non-market values for forests where some degree of diversity remains intact (Costanza et al., 1997; de Groot & van der Meer, 2010, p. 32). For Asia, Guo et al. (2001) conducted a study in China to estimate economic value for water and soil conservation for natural forests, using simulation models and geographic information systems (GIS). The results show that water and soil conservation values were $130 and $766, respectively, per hectare per year in 2020[1], while carbon sequestration accounts for 8.8% of the total indirect economic (non-market) value of natural forests. Caution should be used when applying economic values from other studies. For example, economic values of water and soil conservation are highly site-specific depending on topographical location and the proximity to water resources. Also, the economic values from Guo et al. (2001) were derived for forest protection, which is mainly non-market value, while tree plantations are aimed for timber production with a rotation harvest. For a conservative estimate of non-use value, this study considers only the benefits of carbon sequestration.

[1] Using the exchange rate is CNY 7.1 = $1 in 2020 and the Chinese CPI inflation rate of 1.96% for the year 1997 – 2019 from World Bank (2020) to convert all monetary value into the current US dollars.

2.3 Values of the greenhouse gas emission reduction

Carbon sequestration is a non-market value from forest and plantations. The value is derived from the removal of carbon dioxide from the atmosphere. Climate change has been extensively shown to be linked to an increase in greenhouse gas (or carbon dioxide equivalent) concentration in the atmosphere, resulting in raising the average global temperature, causing physical damage to society. Some regions may gain benefits through increasing crop yields (Cosentino et al., 2012; Tian et al., 2012; and Zhao et al., 2017), and energy-saving for heating (Gonseth et al., 2017) particularly in the upper northern hemisphere. However, the cost pertaining to the temperature rise will be outweighed by such benefits in the long run if there is no intervention (Walthall et al., 2012). Environmental policy by internalizing carbon externalities into the decision-making process became a priority for most countries around the world through international agreements such as the recent Paris Agreement in 2016. To address the benefits of greenhouse gas (GHG) emission reductions in CBA, putting a monetary value on GHG emissions is needed.

Methods for economic valuation of environmental and resource values (including carbon sequestration) are classified into two broad categories; stated-preference and revealed-preference approaches (Tietenberg & Lewis, 2018, p. 78). Stated-preference approaches use survey techniques to ask people directly how much they are willing to pay for a marginal change in environmental quality. Revealed-preference approaches use behavior observation techniques. The latter is widely used for forest recreation by estimating the costs of accessing an environmental resource. This method is mainly linked to human behavior and uses the costs of traveling as a proxy for market prices. Therefore, it cannot estimate non-use values (Hanley & Barbier, 2009).

In the case of non-use value such as GHG emission removal, contingent valuation method (CVM), which is one of stated-preference approaches, is mostly used to estimate willingness to pay (WTP) through a survey for an additional avoidance of damage due to GHG emissions. A key to a successful WTP survey is to have credible information with defensible results if implementing a project. However, the anthropocentric WTP survey has its drawbacks; notably, respondents are mostly subject to their knowledge, perception of issues, occupations, stated political orientation and incomes (Haile & Slangen, 2009; Kotchen et al., 2013; Solecki, 1998; Weber & Stewart, 2009; Winden et al., 2018). More importantly, the damage due to climate change is a global phenomenon. Emissions from one place result in damage in other types of economic values (i.e., food sources), damage in another place, possibly in another part of the world. In other words, it is highly probable that the use value for one group of people is a passive-use value for another group of people. Therefore, it is challenging to elicit the value of protecting the environment from GHG emissions through WTP studies, given that these different types of benefits are vary depending on who is being surveyed.

Some studies try to capture the total economic value using CVM for climate change policy. Americans are willing to pay $71 per household per year[2] for ten (10) years to reduce US emissions of 17% by 2020 (Kotchen et al., 2013), and the results do not vary much among the policy instruments of a cap-and-trade program, a carbon tax, or a GHG regulation. The recent WTP study by the same lead author shows that Americans are willing to pay $190 per household per year[3] to support carbon tax (Kotchen et al., 2017). The substantial difference in WTP results between the studies might be due to the design of the survey where a preference for spending potential carbon tax revenue was added to the latter survey, raising relevancy to people's welfare.

Despite a possible debate on response bias, stated-preference surveys are the only type of method to estimate total economic value, and techniques are widely used in regulatory impact analysis and to evaluate public opinion (Arrow et al., 1993; Johnston et al., 2017). Unfortunately, very few WTP studies to estimate the economic value of GHG emission reduction exist. More importantly, GHG emissions are a global issue that require a global effort to reduce the risk of damage. Therefore, a different approach was developed to elicit the global economic value of carbon dioxide, which is known as the social cost of carbon.

In economics, to elicit appropriate efforts for emission reductions, a marginal abatement cost should be equal to a marginal benefit of the reduction (Hanley & Barbier, 2009). A marginal abatement cost or a marginal cost of GHG mitigations is the additional cost of reducing additional emissions. In contrast, a marginal benefit or a marginal cost of GHG emissions is the additional benefit of damage avoided due to additional GHG emission reduction (see Figure 2.1). The

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[2] The study was done for survey data from 2010 and 2011. The result was estimated at $60 per household per year. By adjusting with an inflation rate of 1.7% for the U.S between 2010 – 2019 (World Bank, 2020b), the WTP in 2020 is $60*(1+0.017)$^{2020-2010}$ or $71.

[3] The survey was in 2016 with the result of $177 per household per year. Using an inflation rate of 1.9% for the US between 2016 – 2019 (World Bank, 2020b), the WTP in 2020 is $177*(1+0.019)$^{2020-2016}$ = $190

quantity at equilibrium becomes a reduction target, and the price at equilibrium is used for climate policies such as carbon pricing.

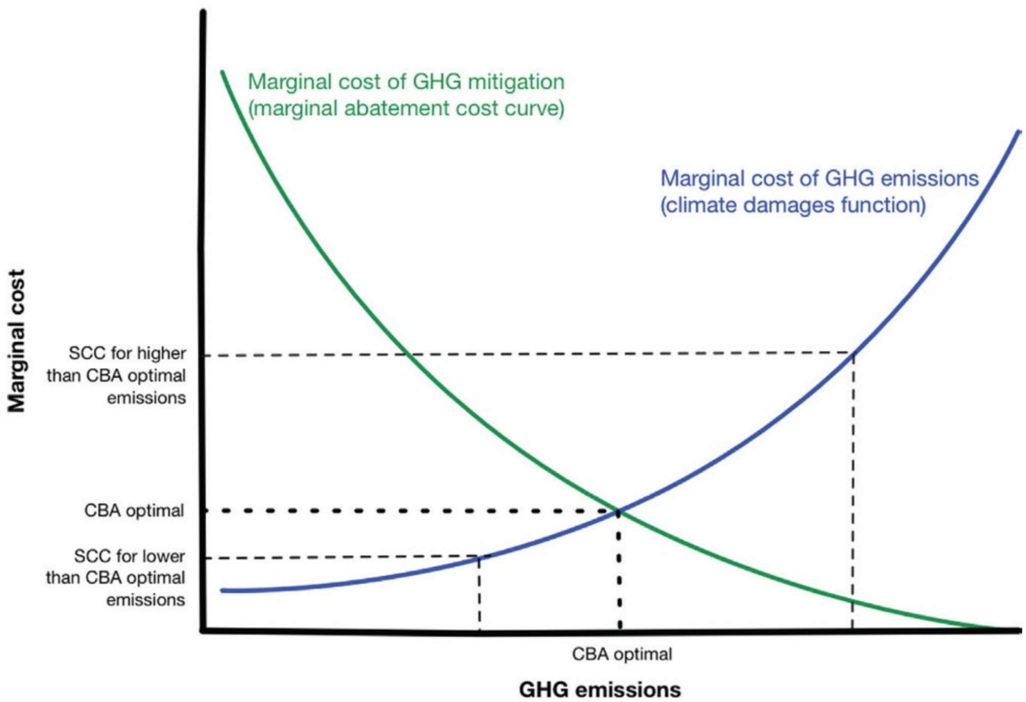

Figure 2.1 Conceptual overview of one period cost-benefit analysis (CBA) applied to the problem of optimal carbon emissions policy and relationship to the social cost of carbon (SCC) (Weyant, 2014).

The social cost of carbon (SCC) is defined as an estimate of the potential economic damage due to emitting one additional ton of greenhouse gases into the atmosphere in present value (Anthoff et al., 2009a, 2009b; Nordhaus, 2008). This is a first-order estimate of the Pigouvian tax necessary for carbon dioxide emissions to reach an efficient level of pollution control (Tol, 2008). The SCC is thus a marginal damage cost used in CBA for climate policies. When a policy decreases GHG emissions, it is then considered to be the benefit of the policy. The main feature of the SCC is the assumption that all damage as the consequence of the increased GHG emissions is captured by the SCC. This is known as the “shadow price,” a monetary value assigned to an abstract commodity with an absence of correct market prices, that is placed on GHG emissions when evaluating the costs and benefits of climate policies (Newbold et al., 2010).

The SCC is estimated based on several assumptions to project future damage due to an additional ton of GHG emissions. The most cited estimation methods are integrated assessment models (IAMs). IAMs are generally comprised of modules; socioeconomic, climate, physical impact, and economic damage modules. Given the update on socioeconomic scenarios, modified climate functions, and damage functions, the SCC has also been updated from time to time. Some studies that are used to do this include Nordhaus (2017), Pindyck (2019), and Tol (2019). Steps to estimate the SCC using IAMs are as follows:

1. Estimate emission trajectories of CO_2 and other GHGs based on socioeconomic (population and GDP) trajectories
2. Model climate impacts due to GHGs using climate models
3. Project physical impacts in different sectors (i.e., sea-level rise and agriculture)
4. Translate environmental impacts into economic damage (i.e., relative to GDP)
5. Discount the future damage to arrive at the present value.

Among the groundbreaking work in developing estimates of the SCC, the Interagency Working Group on the Social Cost of Greenhouse Gases (IWG) under the Obama administration updated the SCC values using IAMs to \$12, \$42, and \$62 per tCO_2 for emissions in 2020 for 5%, 3%, and 2.5% discount rates, respectively (Interagency Working Group, 2016). Using IAMs, the marginal damage cost or the SCC should be theoretically at the equilibrium (i.e., where the marginal abatement cost curve intersects with the marginal benefit of abatement curve). A country may decide to increase or decrease its efforts by setting its SCC higher or lower than the optimal point. Also, the SCC should be increasing over time due to future emissions expected to cause more economic damage, increasing atmospheric carbon stock, and adaptation becomes more costly in response to more significant climate change damage (Environmental Project Agency, 2017).

It is noted that carbon dioxide is classified as a fund pollutant (Tietenberg & Lewis, 2018, p. 336) because it can be absorbed by plant life and the oceans. However, current emissions greatly exceed the assimilative capacity of the environment. The damage can persist and be passed on to future generations. This persistence is a characteristic of stock pollutants. Therefore, carbon dioxide is typically regarded as a stock pollutant, and, thus justifies an increase of the SCC over time to further discourage future emissions.

In the global context, Tol (2008) conducted a meta-analysis of over 200 estimates of the SCC from 47 studies. The results show that the SCC estimate is at \$6.3/tCO_2 on average in 1995. A recent meta-analysis of 58 studies by Wang et al. (2019) shows the higher results. The estimated SCC ranges from \$ -13.36 to \$2,386/tCO_2 with a mean value of \$54.7/tCO_2 from different years of publication; or equals to \$30.78/tCO_2 with a pure rate of time preference at 3% in peer-reviewed studies. Wang et al. (2019) also highlighted that the newer publication year has a higher SCC estimate by order of magnitude.

The estimation of SCC following the IAM procedure was recently done by Ricke et al. (2018). The result shows a high global SCC with a mean value of \$417/tCO_2 using a pure rate of time preference of 2% and a risk aversion of 1.5 (explanations on the pure rate of time preference and the risk aversion is in Section 2.4). This contradicts a recent study done by Tol (2019), where the global SCC estimate is much lower ranging from \$4 to \$15/tCO_2, with the average of \$6.5/tCO_2, using a 1% pure rate of time preference and a risk aversion of 1.0. Further, Ricke et al. (2018) and Tol (2019) also provided results of the estimation of the country-level SCC by calibrating from the global SCC; the estimation uses recent climate model projections, economic damage estimates, and socioeconomic projections for different regions. Results of the country-level SCC from Ricke et al. (2018) show that India, the US and Saudi Arabia are the top three countries with the highest SCC estimates of \$86/tCO_2, \$48/tCO_2, and \$47/tCO_2, respectively. The result is much higher than of Tol (2019) in which India, China, and Ethiopia are the top three countries with the highest SCC estimates of \$1.6/tCO_2, \$0.83/tCO_2, and \$0.32/tCO_2, respectively. The EU and the US have the SCC estimates as small as \$0.09 and \$0.04/tCO_2, respectively (Tol, 2019). Using different approaches produces results that vary widely.

The SCC faces several criticisms such as a lack of human adaptation to climate change, exaggeration of the potential impacts of climate change, lack of probabilities in future emission scenarios, extremely low discount rate, and so on (Idso et al., 2019). According to the Working Group II of the Fifth Assessment Report (AR5), the main issue of SCC estimates is the high uncertainty due to the uncertainty in underlying total damage estimates, future emissions, future climate change, vulnerability, and evaluation as well as disagreement about how to aggregate impacts over time, regions and states of the world. A recent discussion of limitations and drawbacks of SCC from IAMs are summarized in Idso et al. (2019).

Nevertheless, despite the dispersion in SCC estimates among researchers, many economists agree that the value of the SCC is still needed when conducting CBA for climate policies. The SSC can be assigned either by actual estimations, empirical studies, meta-analysis, benefits transfer, or value judgment to ensure that benefits of GHG emission mitigations or costs of GHG emissions do not equal zero.

2.4 Discounting the future: sustainability over very long periods

Previous sections show that to address issues on inter- and intra-temporal equity in CBA, the selection of social discount rates is essential. More importantly, the studies related to discounting costs or benefits for the far future, i.e., SCC derived from the future economic damage of 200 years or more, are highly sensitive to this social discount rate too. Using the 5% discount rate, the SCC was estimated at $12, while using a lower discount rate of 2.5%, the SCC can go up to $62 (Interagency Working Group, 2016). This section defines the social discount rate, methods to estimate the value, criteria used to select components of the social discount rate, and how to address uncertainty for a long-term investment.

Money received today is often preferable to money received in the future: people are impatient, and time involves risk. Hence, a $100 bill today is more valuable than a $100 bill in the future. The difference in value of money from different periods is accounted for by discounting. This concept of discounting is applied in cost-benefit analysis (CBA) to compare values of costs and benefits occurring at different times. In other words, it is done by all future costs and benefits are discounted to the present value. The sum of all present values, which is known as the total present value, is used in CBA to consider whether an investment or environmental project is efficient or not.

Besides the time preference of human beings, society also believes that the future generation will be wealthier and have access to better technology and a better standard of living; therefore, discounting the future is considered appropriate to “level the playing field” across generations (Ramsey, 1928; Spackman, 2004). Public investment has a short, medium, and long term and tends to involve people from different periods: today and the future. To be specific, society today will bear the costs of public investment while benefits are received by society in the future. Hence, there is a specific name for this type of discount rate in economics; it is known as the social discount rate. However, it should be noted that evaluating an investment from the private sector, to maximize financial returns, uses a market interest rate for discounting.

The social discount rate and the market interest rate are not the same, although in discounting calculations, the mathematical machinations may look similar. Typically, the interest rate in private markets for capital is much higher than the social discount rate for social investments, such as environmental projects, mainly because the risk of loss to the individual is greater than the risk to society at large (consider, for example, an individual's expected loss associated with cancer as compared to the health insurance company's loss, where the latter predicts mortality rates using actuarial tables). Also, using a social discount rate of more than a couple percentage points will drive values in the distant future down to virtually nothing, which is tantamount to ignoring the needs of our descendants – that in itself is inconsistent with altruistic characteristics of human societies.

The social discount rate (SDR) has been used in many applied economic contexts. For instance, the determination of the depletion rate of non-renewable resources by Hotelling (1931) and Solow (1947), finding an optimal rate of national savings by Ramsey (1928), and estimating social opportunity cost of public investment by Marglin (1963). The most popular approach used among welfare economists to estimate the social discount rate is the social rate of time preference (SRTP) (Arrow & Kurz, 1970; Feldstein, 1964). The SRTP theoretically is derived from a social welfare function, based on the work of Ramsey (1928). The notion is that policymakers should consider maximizing a social welfare function, which equals the present value of current and future utilities from consumption. In other words, a social welfare function is derived from a utility function which represents social preferences on consumption over a time horizon. In economics, "utility of consumption" is a term used to describe satisfaction from consumption, and it reduces with additional consumption.

Examples of research studies and CBA guidelines using the SRTP include the UK Green Book (2018), Moore & Vining (2018), Harrison (2010), and Hanley & Barbier (2009), to name a few. The SRTP quantifies the weight that society puts on present and future consumption flows. The SRTP using Ramsey's equation is shown as follows:

$$SRTP = \rho + e * g \qquad \text{Eq. (1)}$$

where *SRTP* is the social rate of time preference to estimate the social discount rate, ρ is the pure time preference rate, e is the elasticity of the marginal utility of consumption, and g is the growth rate of per capita consumption. The pure time preference rate reflects *the impatience* of society by discounting the utility of future generations, while $e * g$ represents *the wealth effect*. The pure time preference rate mostly refers to catastrophic risk, with the implication that society may not be able to enjoy consumption. Many economists including Arrow (1999), Evans & Sezer (2004), Kula (1985, 1987), and Pearce & Ulph (1999) suggest the use of a pure time preference rate of 1% to 2.2% to reflect the risk of death due to climate change. However, the widely cited Stern Review justifies the use of 0.1% for a pure time preference rate per year with a consideration of the probability of human race extinction (Stern, 2007). The selection of the pure time preference rate corroborates the earlier discussion that the SRTP is greater than the interest rates in capital markets with individual transactions.

The elasticity of the marginal utility of consumption represents to a percent change in utility compared with a percent change of consumption. The term "utility" has a specific meaning in economics. Utility refers to the amount of satisfaction a person gets from consumption of a certain good and service. Utility can also be monetized by a means of valuing market and non-market values of human-use services. Therefore, utility functions are used to derive willingness to pay. Utility can be expressed in a total and marginal amount. Total utility means total satisfaction or benefit obtained from consumption of goods and services, while marginal utility means the amount of utility gained from the consumption of an additional unit of goods and services. In other words, total utility is an aggregation of marginal utility. Further, marginal utility or marginal benefits is also linked to the derivation of maximized net benefits which is the focus of this CBA. The net benefits use the first equimarginal principle which has different usage from the elasticity of marginal utility of consumption in our CBA study. The first equimarginal principle states that the net benefits are maximized when marginal social cost equals marginal benefit. the detailed explanation is provided in a separate section (section 2.5).

In SDR, the elasticity of the marginal utility of consumption does not refer to individuals but society. The elasticity of the marginal utility of consumption is high if future generations are perceived to have higher real incomes, thus higher consumption. This means that a high elasticity of the marginal utility of consumption results in a high SDR when using Ramsey's equation; society weighs today's consumption greater than the future's consumption. Therefore, it refers to intra-temporal inequality aversion (within a given time period), inter-temporal inequality aversion (across different time periods), or risk aversion (Groom & Maddison Pr, 2019); or the wealth effect when multiplied by the growth rate of consumption (HM Treasury, 2018). A more straightforward definition by Arrow et al. (2004) is: "a social preference for equality of consumption among generations." Empirical studies show that the elasticity of the marginal utility of consumption ranges from 1 to 2 (Arrow, 1999; Boardman et al., 2010; Evans & Sezer, 2004; Kula, 1984). In this report, we use the term "risk aversion" to refer to the elasticity of the marginal utility of consumption.

The growth rate of per capita consumption or the real GDP per capita growth rate is the rate with inflation adjustment. It should be noted that the growth rate of per capita consumption should not be interfered with by any great economic events such as the 2020 financial crisis. This causes uncertainty in applying the historical data on the real GDP per capita growth rate. Gollier (2002) addresses a method to incorporate this uncertainty to be reflected in the social discount rate. Table 2.3 summarizes empirical research done in the past to estimate the social discount rate using the SRTP approach. This shows that the social discount rate is affected by the real growth rate of per capita consumption.

Table 2.3 Empirical research to estimate the social discount rate

No.	Country	ρ	e	g	SRTP	Reference
1	Australia	1.5%	1.7	1.9%	4.7%	(Evans & Sezer, 2004)
2	France	1.0%	1.3	1.9%	3.5%	(Evans & Sezer, 2004)
3	Germany	1.0%	1.4	2.2%	4.1%	(Evans & Sezer, 2004)
4	UK	1.0%	1.5	2.1%	4.2%	(Evans & Sezer, 2004)
5	USA	1.5%	1.4	2.2%	4.6%	(Evans & Sezer, 2004)
6	Japan	1.5%	1.4	2.5%	5.0%	(Evans & Sezer, 2004)
7	India	1.3%	1.64	2.4%	5.2%	(Kula, 2004)
8	Italy	1.0%	1.34	2.1%	3.8%	(Percoco, 2008)
9	Cyprus	1.0%	1.0	3.1%	5.1%	(Evans & Kula, 2011)
10	USA	1.0%	1.35	2.0%	3.7%	(Moore & Vining, 2018)
11	South Korea	1.1%	1.0	4.0%	5.1%	(Sohn, 2019)
12	UK	1.5%	1.0	2.0%	3.5%	(HM Treasury, 2018)
13	Stern Review	0.1%	1.0	1.3%	1.4%	(Stern, 2007)

The UK Green Book (2018) set a social discount rate of 3.5% for public investment (HM Treasury, 2018). When any project has a potential risk to life, a lower rate of 1.5% is justified by excluding the wealth effect, such as would be the case for toxic pollutants. This is the case where social welfare is maximized by saving more lives if mortality rates are astronomically high. It is noted that the Stern Review (2007) has the lowest SDR compared with other researchers by proposing 1.5% of the SDR for environmental policy. This attracts much criticism. Gollier et al., (2008), Nordhaus (2007) and Weitzman (2007) argued that by using the 1.5% SDR, though ethical to avoid damage for future generations, will cause a significant reduction in the incomes of poor people living today, leading to losses of welfare now and in the future. Therefore, they propose the use of a realistic and declining social discount rate, as discussed below. "Realistic," in this case, means that the SDR should take into account the socioeconomic difference in society today and the challenge of institutional structure.

For a long-term public investment, i.e., more than 100 years, a constant SDR might bring costs and benefits close to zero in the present value, especially in a country with a high growth rate of per capita consumption. This means that any public investment for future generations becomes insignificant. To counter this, many researchers advocate adjusting the SDR downward into the future. While the pure time preference rate and the risk aversion are subjective approximations, the growth rate of per capita consumption depends on technological progress and resource accumulations in the economy (Weitzman, 2007). This means that the growth rate of per capita consumption decreases over time due to technological progress and uncertainty about the future. Gollier et al. (2008) have also touted the use of a declining social discount rate because costs and benefits are spreading over a long period of time. For example, Sohn (2019) applies the notion of technological progress to adjust the future growth rate of per capita consumption, resulting in a declining SDR from 5.1% of SDR in an early year to 1.6% in 300 years[4]. Similarly, the Green Book (2018) uses the declining approach for a long-term investment, where the SDR starts to drop from 3.5% in year one to 1.0% in year 300 and more[5]. Unfortunately, SDR estimation is a

[4] The SDR starts at 5.1% for the period of 2000 – 2030, then it falls to 4.1% for the period of 2031 – 2050, followed by 3.1% for the period of 2051 – 2100, and 2.1% for the period of 2101-2200. The last one is 1.6% for the period of 2201-2300.

[5] To illustrate how importance of the discount rate is, we give an example of $100 being discounted for 100 years. The $100 bill in the next 100 years has a value of 0.69 cents today when using a constant 5.1% discount rate, or $3.2 when using a constant 3.5% discount rate, or $2.2 when using a declining discount rate proposed by Sohn (2019).

work in progress. Research studies addressing intergenerational equity and uncertainties, by using either or both mathematical proofs and value judgments, have been emerging. This study can only present the widely cited and recent references. In this analysis, the following points are emphasized.

Selecting the optimal SDR requires a value judgment (for the pure time preference rate and the risk aversion) and an estimate of the future real growth rate of per capita consumption, which is highly uncertain. Value judgments take altruism into consideration because future generations cannot represent themselves in today's decision making. So, it is considered justified to use a zero pure time preference rate. Therefore, the SDR is only based on the real growth rate of per capita consumption and the risk aversion. In the case that a policy with a highly altruism preference, the risk aversion will be set less than 1.0. Thus, the SDR would be less than the real growth rate of per capita consumption. Simply put, society sacrifices today's consumption for future generations. This may not be the case for carbon dioxide emission reduction in small emitting countries, as their progressive climate actions might inevitably result in minimal impact to the global emission reductions. Furthermore, without proper infrastructure, poor people will suffer the most due to the progressive policy. At the same time, the urgency of climate mitigations to reduce potential future damage require immediate actions, as maintaining wealth is not relevant when future generations will be substantially worse off. Given this dilemma, the uncertainty of the SDR can be addressed by using sensitivity analysis.

2.5 Economic efficiency

The results of our CBA study will always yield to positive benefits to society as highlighted in section 1. To interpret the results in a more meaningful manner for decisionmakers, we use the first equimarginal principle together with Pigouvian subsidy rule to provide rationales why government intervention can improve market efficiency. Recall that net benefits are the difference between total benefits and total costs. A marginal cost function is derived from the total cost function, while a marginal benefit function is derived from the total benefit function. A marginal cost function has an upward slope because there are diminishing returns to inputs. For example, adding more workers can reduce their productivity and result in increased costs of the additional unit. Meanwhile a marginal benefit function has a downward slope because an additional consumption of a product yields less satisfaction than a previous unit. In economics, this is called “diminishing marginal utility.”

If there are externalities from implementing a program or a policy, the CBA should take the externalities into account. This can be done by adding externalities on top of private costs and benefits. Therefore, total costs are the sum of private costs and external costs (costs due to negative externalities). Similarly, total benefits are the sum of private benefits and external benefits (benefits due to positive externalities). If the net benefits are not maximized, the allocation of economic resources is not efficient. Market inefficiency occurs when there are some externalities that are not taken into account in the decision. Oftentimes, the private sector aims to maximize their private net benefits by intersecting a marginal private cost curve (MPC) and a marginal private benefit curve (MPB) as shown in Figure 2.2. The market optimal quantity, denoted by q*, is the quantity that the private sector would produce. The blue shaded area in Figure 2.2 denotes the portion of net benefits being accrued not specifically to the private sector but society at large.

Figure 2.2 also depicts market inefficiency, which is represented by the yellow shaded area, which occur when some potential net benefits are not realized due to an inefficient allocation as in this study. This triangle is also known as “deadweight loss,” which is the loss of total welfare. The social optimal quantity, denoted with q**, is calculated by intersecting a marginal private cost curve (MPC) and a marginal social benefit curve (MSB). MSB is the sum of MPB and marginal external benefits. Note that this illustration does not have negative externalities, thus a marginal social cost curve is not used.

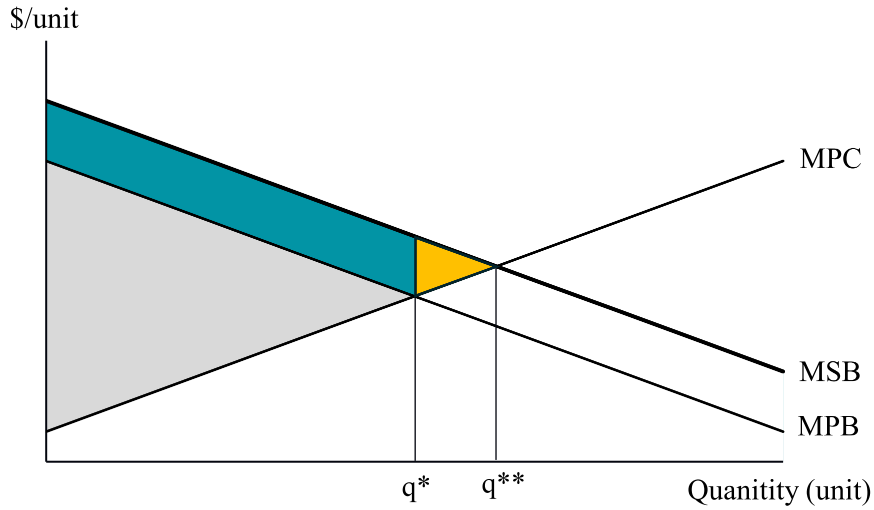

Figure 2.2 Conceptual net benefit maximization.

To incentivize the private sector to produce at the social optimal quantity based on the Pigouvian subsidy rule, the private sector should be subsidized so that the new marginal private cost curve will intersect with the marginal private benefit curve at q**. The subsidy budget is the value of external benefits accrued to society at large.

2.6 Data gaps

The CBA tool is useful in the decision-making process; This helps to decide whether an investment efficiently promotes social welfare. However, based on the literature review, the CBA tool is not extensively used in the private sector, particularly tree plantations. One reason is that the net present value is highly positive for tree plantation investments, and another reason is the lack of guidelines to conduct the CBA in many developing countries. Besides, the challenge to employ CBA is how to quantify the benefits of non-market values, particularly carbon dioxide sequestration. This study uses existing data to quantify CO_2 sequestration for specific tree species, the first of its kind for Lao PDR.

Many assumptions must be made to conduct the CBA and ensure that a conservative estimate of the benefits of carbon dioxide sequestration so as not to oversell an environmental program that is controversial among some policymakers. The main components to estimate the benefits of carbon dioxide sequestration are the social discount rate and the social cost of carbon. So far, there is no regulation or research study to define those components for Lao PDR. The widely cited Ramsey equation may arrive at aa high social discount rate compared to other studies. Alternatively, if using the recommendation from the Stern Review or the UK Green Book with the lower social discount rate, the benefits seem so unrealistically high that it might be challenging to justify for Lao PDR. The choice of SDR requires value judgment for many stakeholders, including ecologists, policy scientists, and economists. It is beyond the current study to promote a particular choice of the SDR, and future investigation on other SDR values is one recommendation of this work. The second component is the social cost of carbon. As no data available on anthropometric climate damage in the country exist, it is impractical to derive the social cost of carbon for the country. The study will use other research studies and other countries' environmental policy as a guidance to assign the ex-ante social cost of carbon for Lao PDR.

3 Study design

This section explains how the CBA was conducted for tree plantation investment with the integration of CO_2 sequestration. The private sector manages most tree plantations in Lao PDR; therefore, some components of CBA in this study take a different approach than a conventional CBA. Eucalyptus and teak plantations were chosen for this study because of the availability of recent data on costs and prices of timber by Maraseni et al. (2018) and Phimmavong et al. (2019). No primary data collection was done in this study. Other necessary and relevant data were gathered from several sources. The following sections provide detailed explanations for each component of the CBA.

3.1 Cost-benefit analysis procedure

Recall the objective of this study is to emphasize the use of CBA in decision making in both public and private sectors, aimed at internalizing social costs and social benefits due to climate-related investment. By doing so, it requires setting the social discount rate lower than a market interest rate, because the purpose is to monetize social welfare, not financial returns on private or even government investment. The main steps of the conventional CBA adapted from Reid et al. (2005) are as follows:

1. Determine the objectives of the CBA
2. Identify the costs and benefit categories
3. Value the costs and benefits
4. Discount and aggregate the costs and benefits
5. Perform a sensitivity analysis
6. Conclude and prepare recommendations

The following sections discuss the study setting, costs, and benefits of the investment, discounting approach, the net present value, and the efficiency criteria to justify government intervention. The last three steps of the CBA are discussed with the results in Chapter 4.

3.2 Description of the study setting

There are two reforestation options: private companies and individual holders. Reforestation practices were presumed to be established on degraded non-cultivated land. Two tree species, eucalyptus (either *E. camaldulensis* or *E. tereticornis*) and teak (*T. grandis*), were selected for this study. Eucalyptus is the most common species planted by multinational companies, mainly in central and southern parts of Lao PDR. Teak plantations, however, have been extensively planted by the smallholders in the northern part (Phimmavong et al., 2009).

There are no available growth and yield data specifically for Lao PDR, this study refers to data on rotation ages and growth rates from the previous studies by Maraseni et al. (2018) and Phimmavong et al. (2019) for teak and eucalyptus in Lao PDR. In order to compare CBA results of different tree species with different rotation ages, thirty years was used as the investment period for both plantations. The consideration of 30-year period for the CBA reflects the current Law on Land (2013): Lao citizens are allowed to lease a piece of land from the Government for 30 years. Input data for CBA are shown in Table 3.1. All explanations of how the input data are selected are in the following sections.

Table 3.1 Input data for the cost benefit analysis

Component	**Teak**	**Eucalyptus**
Mean annual increment (m^3/ha/year)	12.2	28.6
Timber price ($/$m^3$)	93.8 [6]	55.6 [7]
Social cost of carbon ($/t$CO_2$)	1	1
Rotation age (years)	18	7
CO_2 sequestration function (tCO_2)	$CO_2seq = 10.96 * Age^{1.43}$	$CO_2seq = 12.77 * Age^{1.54}$
Concession period (years)	30	30
Nominal interest rate (%)	12	12
Real interest rate (%)	8.3	8.3
Social discount rate (%)	6.9	6.9

[6] $84/$m^3$ in 2017, convert to real price in 2020 using the inflation rate of 3.74%; $84*(1+0.0374)^3$ = $93.8
[7] $48/$m^3$ in 2016, convert to real price in 2020 using the inflation rate of 3.74%; $48*(1+0.0374)^4$ = $55.6

In the CBA, there are two (2) main components: costs and benefits. The cost component in this study considers only the costs of plantations being borne by the private sector. The benefit component includes income from tree harvesting and the economic value of carbon sequestration. Also, the benefit component here does not represent the total economic value from tree plantations, as many non-market values are excluded.

3.3 Costs of tree plantations

Costs of tree plantations for teak and eucalyptus are extracted from previous studies by Maraseni et al. (2018) and Phimmavong et al. (2019). They show that the costs of plantations for eucalyptus are higher than that of teak: $6,333/ha versus $1,149/ha. This difference is explained by the fact that smallholders manage teak plantations, while private companies manage eucalyptus plantations. A private company is required to bear other costs, including a concession payment and development funds for local communities. A smallholder of teak plantations does not pay for harvesting costs, except plantation registration costs. Transportations costs were not included. All costs in the CBA are converted to the real costs by adjusting them with the consumer price index (CPI) inflation rate. Costs of plantations occur every rotation until the end of the concession period. It is assumed that the real costs of plantations do not change over time.

3.4 Benefits of tree plantations

The benefits of tree plantations are categorized into two types: market and non-market. Timber harvesting benefits are market values representing financial returns for an investor, while benefits from carbon sequestration are a non-market value representing social benefits. In many research studies, the term "carbon sequestration;" is measured in units of carbon dioxide (tCO_2), while other studies measure carbon sequestration in units of carbon (tC). For consistency, carbon dioxide (CO_2) sequestration will be used herein to refer to an amount of CO_2 removed from the atmosphere by tree absorption, expressing as tons of carbon dioxide per hectare (tCO_2/ha).

3.4.1 Timber harvest benefits

Timber harvesting benefits stem from selling timber. Two pieces of information are needed to estimate benefits from timber harvest: the price of timber and volume of a tree stand at rotation age.

Trees are priced primarily on timber quality, diameter, and length. Unfortunately, data on prices for teak and eucalyptus in Lao PDR are limited. Nevertheless, growers in northern Lao PDR reported that they did not receive timber prices greater than \$84/m^3 in 2017 for teak (Maraseni et al., 2018). In contrast, the small diameter of teak timber for Africa, America, and Asia are priced at \$124/m^3, \$129/m^3 and \$149/m^3 on average, respectively (Kollert, 2013; Midgley et al., 2015), and the medium-size log price is \$282/m^3 on average in Asia (Midgley et al., 2015). In the case of eucalyptus, it was reported that the timber price at a farm gate (without transporting costs) is \$48/m^3 in 2016 (Phimmavong et al., 2019). Similar to costs, prices are adjusted for inflation to arrive at the real prices of timber in 2020 dollars. Though resource scarcity can drive the real value of timber up through scarcity rents, this study assumes a constant price over a concession period of 30 years to be conservative in the estimation of benefits.

Tree volumes at rotation age are typically estimated using a growth function. To maximize long-term wood production, trees are theoretically harvested at a biological rotation age or when the growth rate, or the mean annual increment (MAI), starts to decline (see Figure A.5). The MAI is calculated by dividing yield with stand age. Generally, teak has the highest MAI at the age of 40 - 60 years (Ball et al., 1999), while the MAI is highest for eucalyptus at 7-15 years (Lamprecht, 1990) based on its locations, spacing, site properties, and plantation management. In the case of developing countries, selected rotation age tends to be shorter than biological rotation age. Presumably, the private owners aim to maximize financial returns based on current timber prices. For example, the reported rotation age for teak in Lao PDR is 18 – 24 years while the rotation age for eucalyptus is 7 years (Maraseni et al., 2018; Phimmavong et al., 2019).

Data on rotation age and growth rate from several works of literature are summarized in Table 3.2. Unfortunately, it is not currently possible to obtain functions for yield or growth rate by using regression analysis due to discrepancies in reported characteristics. Studies on growth and yields for teak and eucalyptus are also limited in Lao PDR. Therefore, this study uses data provided by previous literature.

This study estimates the volume of tree stands at a rotation by multiplying MAI with a harvesting age. MAI for teak is 12.2 m^3/ha/year for the 18-year rotation age, while 28.6 m^3/ha/year of MAI is selected for eucalyptus for the 7-year rotation age.

Table 3.2 Rotation and growth data for teak and eucalyptus

Species	**Rotation age (years)**	**Mean annual increment (m^3/ha/year)**	**Reference**
T. grandis	14	10.7 – 13.3	(Zahabu et al., 2015), Tanzania
T. grandis	18 - 24	9.3 - 12.2	(Maraseni et al., 2018), Laos
T. grandis	40	9.3	(Pandey & Brown, 2000), Costa Rica
T. grandis	60 – 70	6 – 9	(Pandey, 1983), India and Nigeria
T. grandis	60 – 70	12 – 15	(Pandey, 1983), Indonesia
T. grandis	60 – 80	4 – 8	(Evans, 1992), India
Eucalyptus spp.	7	28.6	(Phimmavong et al., 2019), Laos
E. camaldulensis	10	15 – 18	(Pohjonen & Pukkala, 1994); Thailand
E. camaldulensis	10 – 20	5 – 10	(Evans, 1992); Dry tropics
E. camaldulensis	10 – 20	30	(Evans, 1992); Moist tropics
E. tereticornis and *E. camaldulensis*	7	15 – 24	(Harwood & Nambiar, 2014), SE Asia

3.4.2 Benefits from CO_2 sequestration

In order to elicit the value of benefits from CO_2 sequestration, two pieces of information are required: (1) CO_2 sequestration in units of tCO_2 per hectare; and (2) the value of carbon dioxide or the social cost of carbon (SCC) in dollars per tCO_2. There are two approaches to estimate CO_2 sequestration in trees. The first approach is to estimate based on tree yields. However, data on tree yields (or tree volumes or MAI) are reported in a data range as shown in Table 3.2, and a regression analysis using such data cannot be done, as highlighted in section 3.4.1. The second approach is to estimate based on carbon content inside a tree. There are some studies providing carbon pool stock stored in tree volumes of teak and eucalyptus for different stand ages (see Table A.7 and Table A.8 in the Appendix). This allows us to estimate CO_2 sequestration in units of tCO_2 per hectare by multiplying the carbon pool stock, which is in a unit of tC per hectare, by a unit convertor (12 mass units of C = 44 mass units of CO_2). Regression analysis was done using amount of CO_2 sequestration as the dependent variable and stand age of tree as independent variable. A log-log functional form was selected to reflect zero sequestration when tree is first planted. The mathematical model for regression analysis is shown in Eq. (2).

$$\ln CO_2seq = \mathrm{b}_0 + \mathrm{b}_1 \ln Age \qquad \text{Eq. (2)}$$

where CO_2seq is CO_2 sequestration (tCO_2/ha), Age is the stand age of tree (years), and b_0 and b_1 are coefficients. The regression results have a high R-squared of 0.87 and 0.70 for teak and eucalyptus, respectively. p-values for t-test for all coefficients as well as p-values for F-test are less than 0.05, which means that estimated coefficients are statistically significant at a 95% confidence level. The regression models for both tree species are also an unbiased estimator based on tests for normality, heteroscedasticity, non-linearity and model specification. The log-log model was retransformed into a linear-power function using smearing retransformation (see Appendix A.2 for a detailed analysis). The results of CO_2 sequestration functions are shown below.

CO_2 sequestration for teak: $$CO_2seq = 10.96 * Age^{1.43} \qquad \text{Eq. (3)}$$

CO_2 sequestration for eucalyptus: $$CO_2seq = 12.77 * Age^{1.54} \qquad \text{Eq. (4)}$$

The above functions show that at a stand age of one, eucalyptus sequestrates CO_2 of 12.77 tCO_2/ha, which is higher than 10.96 tCO_2/ha for teak. Due to a higher power number[8], eucalyptus also sequestrates more than teak does as a stand age increases. To calculate the economic value of CO_2 sequestration in a value of dollars per hectare, an amount of CO_2 sequestration based on a stand age is calculated using the above function and then multiplied by the value of SCC.

In the case of SCC estimation, the SCC estimate is ambiguous and highly controversial even for the global estimates. However, it is an essential metric for climate policies. Without SCC, the benefits of CO_2 sequestration from tree plantations become zero. In practice, many countries set their ex-ante SCC, specifically for carbon tax rates, ranged from \$3 to \$168/tCO_2 in 2015 (World Bank Group, 2017, p. 90). The SCC is expected to increase over time based on a country's effort

[8] 1.54 is for eucalyptus and 1.43 is for teak, based on Eq. (4) and Eq. (3), respectively.

to reduce carbon dioxide. In the case of Lao PDR, using a country-level SCC estimated by Ricke et al. (2018), results in a SCC less than \$1/tCO_2, which is on the very low end of the spectrum. Although the real figure is unknown, this study assumes \$1/tCO_2 for CO_2 sequestration from tree plantations as the base case to be conservative in the estimate of benefits. A sensitivity analysis is done later to evaluate the impact of the change in the SCC.

In addition to the estimation of the monetary value of CO_2 sequestration benefits, it needs to be understood that the land policy can act as a constraint for trees to sequestrate. The relationship of predicted CO_2 sequestration and rotation age with consideration of a 30-year concession is shown in Figure 3.1. Apparently, when a selection rotation age, of any tree species, approaches a limit of 30 years, the total as well as average CO_2 sequestration potential dwindles. Also, Some selections of rotation age result in zero CO_2 sequestration at the end of year 30. Therefore, the predicted CO_2 sequestration for 30 years with different rotation ages has a non-smooth curve, as shown in Figure 3.1. The estimation here was carefully done within a range of sample data: 1 to 20 years for teak and 3 to 10 years for eucalyptus. This is to avoid uncertainty, mainly when the sample data range does not cover the biological rotation age. Table A.17 in the Appendix provides a full calculation of CO_2 sequestration with different rotation ages.

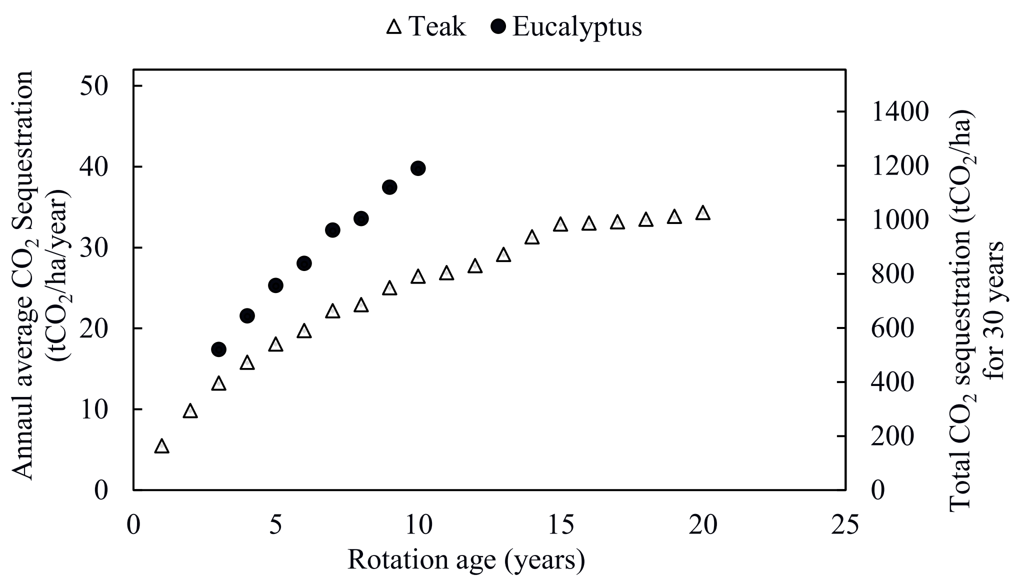

Figure 3.1 Relationships of predicted CO_2 sequestration and rotation age with a 30-year concession as a constraint

It can be concluded that the 30-year concession period may not allow trees to grow and reach their potential. Similarly, the selection of rotation age also affects the maximum CO_2 sequestration. It is unsurprising to find eucalyptus has more CO_2 sequestration potential than teak given the same rotation age.

Given the concession of 30 years by using a rotation age of teak and eucalyptus plantations of 18 years and 7 years, respectively, it can be concluded that CO_2 is sequestrated from the atmosphere at about 1001.5 tCO_2/ha for teak plantations and 961.8 tCO_2/ha for eucalyptus plantations. The similar sequestration values are due to the contrasting attributes of the low growth rate with the longer selected rotation age for teak plantations compared with the high growth rate but the shorter selected rotation age for eucalyptus plantations. On average, the annual CO_2 sequestration for both plantations is 32 tCO_2/ha/year, while the CO_2 sequestration of natural forests is only 2.45 tCO_2/ha/year based on a study done by Yen & Wang (2013) in Taiwan. Thus, society gets more benefits from tree plantations than natural plantations in terms of CO_2 sequestration potential.

3.5 Discounting approach

Unlike the World Bank's recommended discount rate of 10 to 12% for project appraisal in developing countries (Bonzanigo & Kalra, 2014), this study employs the dual discounting approach to discount financial returns and benefits of CO_2 sequestration separately. There are two discount rates used in this CBA; the real interest rate for discounting cash flows of financial returns and the growth-rate-adjusted social discount rate (SDR) for discounting benefits of CO_2 sequestration. The real interest rate is calculated by subtracting the inflation rate from the nominal interest rate. A nominal interest rate of 12% was used based on the borrowing interest rate from the Agriculture Promotion Bank, which is the only state bank that gives loans for agriculture and forestry investment projects in Lao PDR. The inflation rate, estimated by using the consumer price index (CPI) from 2010 – 2019, is 3.74% on average (Bank of Lao PDR [BOL], n.d.), is calculated from the difference of CPI of the current year and the previous year, then divided by the previous CPI. Thus, the real interest rate of 8.3% was applied for financial analysis. The high real interest rate in developing countries such as Lao PDR can be explained by the limited availability of credit provided by banks and a default risk inducing banks to charge a high interest rate for borrowing.

In contrast, the SDR is estimated based on the consumption discount rate equation developed by Ramsey (1928). The SDR estimate represents intertemporal equity; how much society weighs today's consumption compared to the consumption of future generations. It is also assumed to differ from country to country. By using Ramsey's equation, the SDR in developing countries is expected to be higher than in developed countries. This is not entirely associated with higher risks due to unpredictable politics in developing countries, but mainly due to a higher real GDP per capita growth rate in emerging economies. Based on nine-year data on real GDP per capita from 2010 - 2019 in a local currency, Lao PDR has a real GDP per capita growth rate of 5.9% on average. Therefore, according to Ramsey's equation, with the assumptions of the pure rate of time preference at 1.0% and the wealth effect at 1.0, the social discount rate is 6.9%[9]. The social discount rate of 6.9% is high compared with studies done in other developed and developing countries, which will lead to a more conservative estimate of intertemporal benefits. This 6.9% SDR is still lower than a general SDR applied by developing countries, which ranges between 8-15% (Zhuang et al., 2007). This high SDR reflects the perception of the social opportunity cost of public funds and the consideration of intergenerational equity. To contrast, the lower SDR of 1.5% and 3.5% is also used to illustrate possible benefits that can be obtained. The 1.5% SDR represents the consideration of only a pure rate of time preference to reflect social altruism toward the future, while the 3.5% SDR is to represent the value as if it is assessed for developed countries.

3.6 Net present value

In general, an investment is efficient when benefits are greater than costs. In CBA, under the social welfare condition, an investment maximizes social welfare when social benefits are greater than social costs in present value terms, also known as positive net present value (NPV). The NPV is a summation of the present value of all future benefits less the present value of all future costs. To show how the dual discounting approach is used, benefits of CO_2 sequestration and revenues from timber sales are treated separately, given different rates of discounting. The real interest rate is used to discount revenues, while the SDR is used to discount the benefits of CO_2 sequestration. Thus, the calculation of the net present value for this study is shown in Eq. (5).

[9] 1.0% + 1.0 * 5.9%

$$NPV = \sum_{t=0}^{T} \frac{R_t}{(1+r)^t} - \sum_{t=0}^{T} \frac{C_t}{(1+r)^t} + \sum_{t=0}^{T} \frac{B_t}{(1+SDR)^t} \quad \text{Eq. (5)}$$

where *NPV* is the net present value (dollars), R_t is revenues at time *t* (dollars), C_t is costs at time *t* (dollars), B_t is benefits from CO_2 sequestration at time *t* (dollars), *r* is the real interest rate (%), *SDR* is the social discount rate (%), *t* is a number of year (year), and *T* is the total period (years).

The private rate of return and the social rate of return are also used to represent the internal rate of return (IRR) for the private sector and the public sector. IRR is a measure of the expected rate of return from the investment projects at which NPV is equal to zero. The social rate of return (SRR) refers to the rate of return with consideration of externalities.

The land expectation value (LEV), which is another indicator for financial analysis, is a standard discounted cash flow (DCF) technique to value timberland. This allows the estimation of the value of bare land for perpetuity for even-aged rotations. LEV is suitable for a long-term evaluation, whereas NPV is for a short-term evaluation rotation of 5 to 20 years. It is noted that the LEV formula assumes constant dollars and a real interest rate.

$$NFV = \sum_{t=0}^{T} R_t * (1+r)^t - \sum_{t=0}^{T} C_t * (1+r)^t \quad \text{Eq. (6)}$$

$$LEV = \frac{NFV}{(1+r)^t - 1} \quad \text{Eq. (7)}$$

where *LEV* is land expectation value (dollars), and *NFV* is the net future value of one timber rotation (dollars). The LEV refers to the financial value of timberland or financial returns for a long-term investment. Thus, the non-market value is not included. All other formulas used are provided in Appendix A.4. All monetary values in this study are in 2020 dollars (USD).

3.7 Efficiency in government intervention

The NPV is a means to decide whether a project should proceed or not, regardless of the public or private sector. However, the decision of government intervention in a private market considers additional elements. The deviations between social returns and private returns have been used to justify state intervention since Pigou (1920) was published. The difference in social returns and private returns is due to externalities (benefit of carbon sequestration from plantations). Government intervention is a means to encourage or discourage producers who create externalities. The exclusion of negative externalities can cause a market failure while the exclusion of positive externalities results in underinvestment for social benefits. Figure A.4 in the Appendix illustrates a government intervention rule proposed by Warner (2013) for any type of investment with negative or positive externalities. In our study, carbon sequestration is a positive externality. Therefore, criteria for government intervention in private tree plantations adapted from Warner (2013) are:

(1) The social rate of return is higher than the private rate of return; and
(2) The private rate of return is less than the market interest rate.

The second criterion demonstrates that if the private rate of return is higher than the market interest rate, the private sector will voluntarily invest. Government intervention may not create much difference in social returns. When the government intervention criteria are met, the next question is how to determine the budget for government intervention. By applying the first equimarginal principle explained in section 2.5, the inclusion of the external benefits due to carbon sequestration results in the net social benefits being higher than the net private benefits. Therefore, to incentivize the private sector to maximize the net social benefits instead of the net private benefits, the Pigouvian subsidy rule suggests that the private sector should be subsidized with the same value of external benefits being accrued to society at large. In other words, the budget for government intervention equals the value of external benefits. The subsidy payment can be in many forms, and our study proposes the subsidy payment is generated by regulation improvement to increase the private rate of returns.

4 Results and Discussions

The results of CBA provided in this section include (1) the cost-benefit analysis for private tree plantations for two tree species (teak and eucalyptus) in Lao PDR, (2) the impact of the change in social discount rate and social cost of carbon on the net present values of non-market benefits, and (3) the result justifications that take into account different policy and anticipated damage scenarios which will affect policy priority and proposed budget of government intervention. Discussions on why the results of this study are not only defensible but conservative are also provided.

4.1 Cost-benefit analysis for private tree plantations

Unlike studies done by Maraseni et al. (2018) and Phimmavong et al. (2019), this study considers the 30-year concession period when conducting CBA. This allows the comparison of results from different tree species with different rotation ages. The results, including costs, benefits, net benefits, net present value (NPV), private rate of return, social rate of return, and land expectation value (LEV) for both plantations, are shown in Table 4.1. Also, the social NPV, which is the sum of market NPV and non-market NPV, is provided (see Appendix A.1 for technical details on CBA).

Table 4.1 Results of the cost-benefit analysis over 30 years (in 2020)

	Teak 18-year rotation age			**Eucalyptus 7-year rotation age**		
Timber yield (m^3/ha)			354			772
CO_2 sequestration (tCO_2/ha)			1,002			962
	Market	Non-market	Total	Market	Non-market	Total
Cost	$2,470	0	$2,470	$19,791	0	$19,791
Benefit	$33,180	$1,002	$34,182	$42,930	$962	$43,891
Net benefit	$30,710	$1,002	$31,711	$23,139	$962	$24,101
Net present value	$4,696	$397	$5,093	$4,574	$391	$4,965
Rate of return	18.0%	-	19.0%	18.0%	-	18.7%
Land expectation value	$6,176	-	-	$10,731	-	-

When interpreting the results, we use the term “private” to refer to the analysis that considers only market value, and the term “social” to refer to the analysis that considers both market and non-market value. Also, values from other studies were adjusted into 2020 dollars. The interpretation of the results follows.

Timber yields and CO_2 *sequestration*

Being characteristically fast growing, eucalyptus plantations yield higher wood production of 772 m^3/ha compared to teak with a timber yield of 354 m^3/ha for a 30-year plantation; though the rotation time period for eucalyptus is 7 years, lower than that of teak which is 18 years. Due to more frequent rotations, eucalyptus plantations can sequestrate slightly less CO_2 from the atmosphere than teak plantations, at 962 tCO_2/ha and 1,002 tCO_2/ha respectively. However, using a different rotation age can vary the timber yields and CO_2 sequestration. The interpretation here only considers the current practice of the rotation age selection based on previous studies.

There are two possible outcomes to inform policymakers. First, given the current objective of the Lao Government allocating 1.2 million hectares with the goal to increase forest cover as well as wood production, eucalyptus investments should be a priority. Second, if the government decides to set CO_2 sequestration as the main objective for tree plantations, possibly in the near future, then it will be more beneficial to consider enhancing the teak plantation industries. Nevertheless, this distinction between plantation priorities still needs further exploration—for instance, priorities can be ranked based on the probability of success of government intervention for different tree markets. Teak plantations are primarily in the northern part of Lao PDR, while eucalyptus plantations are located mostly in the central and southern parts of Lao PDR. Each location has unique characteristics in terms of social-economic and cultural aspects. When converting timber yields and CO_2 sequestration into a monetary benefit, similar interpretations were reached, where teak yields a higher value of CO_2 sequestration and eucalyptus yields a higher value of wood production (see the interpretation of benefits in the following sub-section).

Net benefits

Net benefit is the difference between benefits and costs from an investment. The results of this study show higher social net benefits compared to private net benefits. The social net benefits are $31,711/ha and $24,101/ha for teak and eucalyptus plantations, respectively. This is due to the internalization of non-market value - CO_2 sequestration. The non-market value for CO_2

sequestration from both tree species is not much different; $1,002/ha for teak and $962/ha for eucalyptus, which is about 3.2% and 4.0% of total benefits[10] – not a trivial percentage. Therefore, by taking an average of net benefits from both types of plantations, society can get net benefits from tree plantations around $930/ha/year[11] for 30 years, where the benefit of carbon sequestration accounts for 3.5% of the total net benefit. Compared to results from a study conducted in China, the total net benefit for tree plantations from our study is lower than the total net benefit from Guo et al. (2001) for natural forests, which is $1,199/ha/year. Market benefits are the main component of the total net benefits of our study, while the total net benefits estimated by Guo et al. (2001) were largely derived from non-market values. The authors did not only include benefits of carbon sequestration, but also non-market benefits from soil and water regulations.

Net present value (NPV)

It is not surprising to find positive private NPV (or market NPV) for teak and eucalyptus plantations, which are $4,696/ha and $4,574/ha, respectively. The positive market NPV is also found in previous studies (Maraseni et al., 2018; Phimmavong et al., 2019). A graph to compare the results of this study to previous studies can be found in Figure A.3 in the Appendix[12]. For a long-term evaluation, it shows that the LEV for eucalyptus is higher compared with teak: $10,731/ha and $6,176/ha. Note that the LEV is a means to measure for financial analysis only; thus, it is only calculated from market value. The difference of LEV implies that eucalyptus plantations provide a higher long-term return on investment. However, caution should be taken into account when translating the LEV results. This analysis did not consider the possible increase in the real price of timber in the future, especially for teak. Given a slow growth rate of teak, and a likely higher future demand, the real price of teak is expected to increase faster than that of eucalyptus, because of the scarcity in the future. The long-term value of teak plantations may be higher than $6,176/ha.

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[10] ($1,002/$31,711) * 100 = 3.15% and ($962/$24,101) * 100 = 3.99%.

[11] ($31,711 + $24,101)/2/30 = $930.

[12] Technically, the results of this study cannot be compared exactly with the previous studies, because different approaches are used. Previous studies use a nominal interest rate to discount nominal costs and revenues, while this study use a real interest rate to discount real costs and revenues. Most importantly, the main difference is a time parameter. This study added a 30-year concession period. Nevertheless, the results of this study do show some alignment with previous studies – a positive NPV.

The social NPV is slightly higher than the private NPV for both plantations, similar to the interpretation of net benefits earlier, due to the addition of non-market benefits. The social NPVs for teak and eucalyptus are $5,093/ha and $4,965/ha, respectively. The non-market value, CO_2 sequestration, from both tree species is not much different, with an average of $394/ha in a present term, or about 7.8% of the average social NPV[13].

Rate of returns

A similar conclusion is obtained for the rate of returns, in which the social rate of return (SRR) is slightly higher than the private rate of return due to the integration of non-market value. The SRR is 19% and 18.7% for teak and eucalyptus plantations, while the private rate of returns is 18.0% for both plantations. The SRR is expected to be higher than what we use in this study if other non-market values are included.

Recall government intervention is efficient when the SRR is greater than the private rate of returns (first criterion), and the private rate of return is less than the market interest rate (second criterion). Given the current study, it can be said that it is rational for the government to intervene in private tree plantations, as it meets the first criterion. However, the intervention may be subject to less priority from a government's perspective. Because the private rate of return is higher than the market real interest rate of 8.3%, the private sector will voluntarily invest in tree plantations regardless of additional government support. Our justification is that government intervention by improving systems and regulations can increase the private rate of return and eventually incentivize the private sector to plant more trees.

4.2 Impact of social cost of carbon and social discount rate

Input data to the CBA are subject to uncertainty, such as timber price, the market interest rate, the inflation rate, the real growth rate of per capita consumption (which is used to estimate the SDR) and so on. This study only considers uncertainty related to the value of non-market benefits. The reason is that the non-market benefits are used to determine the budget for government intervention. Recall the SCC and SDR only affect the non-market component, and the real growth

[13] ($5,093 + $4,965) / 2 = $5,029; and $394/$5,029 * 100 = 7.8%.

rate of per capita income is used to estimate the SDR. Thus, a sensitivity analysis was performed for the non-market NPV and SRR given the change in the SCC and the growth rate of per capita consumption.

Impact of SCC on the non-market NPV

The ex-ante SCC is set at $1/t$CO_2$. A sensitivity analysis was done by changing the percentage change in SCC. Table 4.2 shows the non-market NPV with changes in the SCC. It is not surprising to find a linear relationship between the SCC and the non-market NPV, because the non-market NPV uses a constant SCC in the calculation. It can be concluded that an increase in the SCC results in an increase in the non-market NPV, and vice versa, in an equal magnitude. A ten percent increase of the SCC will increase the non-market NPV by ten percent.

Table 4.2 Impact of social cost of carbon (SCC) on the net present value of non-market benefits

SCC (\$/tCO_2) (% change of SCC)	0.8 (-20%)	0.9 (-10%)	1 (0%)	1.1 (+10%)	1.2 (+20%)
Teak	\$318 (-20%)	\$357 (-10%)	\$397 (0%)	\$437 (+10%)	\$476 (+20%)
Eucalyptus	\$313 (-20%)	\$352 (-10%)	\$391 (0%)	\$430 (+10%)	\$469 (+20%)

Note: percent differences to the base case are in parenthesis.

Impact of the growth rate of per capita consumption on the non-market NPV

Based on macroeconomic data, the real growth rate of per capita consumption for Lao PDR ranges between 3.1% to 9.3%, with an average of 5.9% (BOL, n.d.) (see Table A.15 in the Appendix). A sensitivity analysis was done for the change of growth rate of per capita consumption, as shown in Table 4.3. The SDR was recalculated based on Ramsey's equation (a pure rate of time preference of 1.0% and the risk aversion of 1.0). The non-market NPV was also recalculated. The results show that the non-market NPV for teak plantations is slightly more sensitive to the change of growth rate of per capita consumption than eucalyptus plantations. When the growth rate of per capita consumption increases by 10%, the non-market NPV decreased by 6.3% and 5.9% for teak and eucalyptus, respectively.

Table 4.3 Impact of the growth rate of per capita consumption on the net present value (NPV) of non-market component

SDR (%) (% change of growth rate of per capita consumption)	5.72 (-20%)	6.31 (-10%)	6.90 (0%)	7.49 (+10%)	8.79 (+20%)
Teak	$455 (+14.6%)	$424 (+6.8%)	$397 (0%)	$372 (-6.3%)	$325 (-18.1%)
Eucalyptus	$445 (+13.8%)	$416 (+6.4%)	$391 (0%)	$368 (-5.9%)	$324 (-17.1%)

Note: percent differences to the base case are in parenthesis.

Impact of the SCC on the SRR

The social rate of return (SRR) was recalculated with the change in the SCC by holding other input parameters constant. By doing so, it is expected that only the non-market component of the social NPV is changed. The market NPV remains that same, which is $4,696/ha and $4,574/ha for teak and eucalyptus, respectively. The results are in Table 4.4. Note that the SRR is calculated from net benefits (not present values of net benefits). Therefore, the change of SDR does not affect the SRR. The results show that the SRR is not sensitive to the SCC. A ten (10) percent increase in the SCC results in a 0.5 percent increase in the SRR for teak plantations and 0.38% for eucalyptus plantations. This is due to the benefits of the non-market value of tree plantations is minimal compared to market value; on average, the non-market value accounts for 3.5% of the total net benefits or 7.8% of the social net present values.

Table 4.4 Impact of the social cost of carbon (SCC) on the social rate of return (SRR)

SCC ($/t$CO_2$) (% change of SCC)	0.8 (-20%)	0.9 (-10%)	1 (0%)	1.1 (+10%)	1.2 (+20%)
Teak	18.82% (-1.00%)	18.91% (-0.50%)	19.01% (0%)	19.10% (+0.50%)	19.20% (+1.00%)
Eucalyptus	18.52% (-0.76%)	18.59% (-0.38%)	18.67% (0%)	18.74% (+0.38%)	18.81% (+0.76%)

Note: percent differences to the base case are in parenthesis.

4.3 Result justifications

The main justification of the current study is the fact that existing problems related to tree plantations are presumed to take a long time to solve. This is a common policy in poor and developing countries, but other social-economic issues often get a higher priority. This study aims to advocate to the government the need for intervention to provide incentives for private investors to plant more trees. Non-market value is accrued to society and, as shown earlier, sensitive to the choice of SCC and SDR. For simplicity. We take four (4) scenarios for our result justifications. Each scenario uses different SDR and SCC resulting to differences in the non-market NPV as shown in Table 4.5.

(1) the altruism scenario with relatively high damage due to climate change
(2) the altruism scenario with relatively low damage due to climate change
(3) the social welfare balance scenario with relatively high damage due to climate change
(4) the social welfare balance scenario with relatively low damage due to climate change

Table 4.5 the non-market NPV associated with different scenarios

Scenario	SDR	SCC	Non-market NPV
1	1.5%	$1/tCO_2$	$780/ha
2	1.5%	$5/tCO_2$	$3901/ha
3	6.9%	$1/tCO_2$	$394/ha
4	6.9%	$5/tCO_2$	$1970/ha

The NPV of non-market benefits stemming from tree plantations associated with the considered scenarios. When the SCC is set at $1/tCO_2$, by using 1.5% SDR the non-market NPV is $780/ha while using 6.9% SDR the non-market NPV is $394/ha. When the SCC is $5/tCO_2$, the non-market NPV increases by five times. Detailed analysis can be found in Table A.5, Table A.6, and Table A.18 in the Appendix. The SDR of 1.5% represents the altruism scenario, while the SDR of 6.9% represents the social welfare balance scenario. The lowest non-market NPV is $394/ha for tree plantations on average, while the highest non-market NPV is 3,901/ha.

Note that the 3.5% SDR provides the mid-point between the 1.5% and 6.9% SDR for the non-market NPV, as shown in Table A.18 in the Appendix, which is $591/ha for the SCC of $1/tCO_2 and \$2,955/ha for the SCC of \$5/tCO_2. This can represent the average value between the altruism scenario and the social welfare balance scenario.

The choice of SDR

Recall that in Ramsey's equation, the SDR is calculated based on a pure rate of time preference, an elasticity of the marginal utility of consumption (a risk aversion), and a growth rate of per capita income. To maintain social welfare, the 6.9% SDR is used. The 1.5% SDR represents only a pure rate of time preference of 1.5%, excluding the wealth effect (a real growth rate of per capita consumption). By using the 1.5% SDR in evaluating an environmental policy, the sacrifice of today's welfare by investing heavily now for the benefits of future generations is accounted for. Since the plantation investment in this study is a short to medium term, and the non-market value is moderately sensitive to the choice of SDR, the 6.9% is also justified. The 1.5% SDR can be used in CBA for a long-term investment by using a declining discounting approach as an example from Sohn (2019). For instance, 6.9% for 0 – 50 years, 3.5% for 50 – 100 and 1.5% for 100+ years.

The choice of SCC

There are several non-market values of tree plantations such as air quality, carbon sequestration, water quality regulation, natural hazard regulation, and erosion prevention. Unfortunately, research of non-market values of tree plantations in Lao PDR or Southeast Asia is limited. Since non-market values are subject to local preference and socio-economic settings, it is somewhat impractical to use a benefit transfer by taking economic values from other literature (mainly from developed countries) to include in this study. This requires data calibration beyond an economic adjustment. People in developed countries value ecosystem services differently from people in developing countries. Non-market value for this study only refers to carbon sequestration benefits and does not refer as a proxy to represent the whole spectrum of non-market values. The benefits of non-market value could be substantially higher than the results of this study. However, study assumptions were made to keep the analysis conservative in the estimation of benefits.

Practically, the SCC has already been applied in the form of emission trading systems or carbon taxes, which are called carbon pricing initiatives. Theoretically, carbon taxes should be equal to the SCC to limit GHG emissions. A carbon tax is a Pigouvian tax to encourage social responsibility by creating the incentive to consume less fossil fuel. A carbon tax is a means to adjust carbon emissions to an optimal quantity by considering negative externalities (GHG emission). Therefore, this basis can be used to find the current SCC used in other parts of the world. In 2019, 7 out of 29 countries who implemented carbon taxes reported carbon prices between \$1 to \$5/tCO_2, including Japan (\$2.6/tCO_2) and Singapore (\$3.6/tCO_2) (World Bank, 2019). The rest of the 22 countries are mainly developed countries, and the carbon taxes are as high as \$121/tCO_2 in Sweden. Though prices in carbon pricing initiatives are not necessarily comparable, due to different sectors covered and fluctuating exchange rates, it provides an intuition on the price range of the SCC. Given that, it is reasonable to choose the SCC for Lao PDR between \$1 to \$5/tCO_2.

In conclusion, we suggest that the environmental policy in Lao PDR should use the social welfare balance with relatively low damage as a minimum requirement for evaluating a short-term tree plantation investment. The non-market value of \$394/ha from tree plantations is also appropriate to use as the basis to advocate for government intervention of tree plantation markets in Lao PDR. Higher values could be justified depending on the environmental policy in the country. Alternatively, this is the lowest unit value supported by the best studies currently available.

5 Conclusions

Government interventions could potentially improve the efficiency of private investment. The current financial analysis for tree plantations in Lao PDR shows high returns on investment. However, there are many issues related to the investment, including high upfront costs of plantations, poor quality of timber, lack of plantation management, and timber prices controlled by wood manufactures, to name a few. Proposed interventions are thoroughly discussed in recent technical studies, including Maraseni et al. (2018) and Phimmavong et al. (2019). For a sound policy, the Government needs to know how much of the budget is required to invest in improving the efficiency of timber markets.

This study integrates the social benefits of tree plantations. Tree plantations provide financial returns to an investor - in this case, the private sector - while also providing social benefits, such as carbon dioxide removal from the atmosphere, resulting in cleaner air and reducing the risk of global climate change damage, which accrue to society. Without this recognition of social benefits, the Government may underinvest in the tree plantation sector.

Efficiency criteria for government intervention were applied, and the results suggest that there is a positive externality to society from private tree plantations. Government intervention can help increase the private rate of return by improving existing infrastructure and regulations to incentivize the private sector to plant more trees. We use the first equimarginal principle of economics to rationalize the budget for government intervention. The principle says that social net benefits are maximized when the marginal benefit equals the marginal cost. In private tree plantations, the costs and incomes are accrued to the private sector. A positive externality from non-market value such as carbon sequestration is accrued to society. Thus, the non-market value can be used as a basis to allocate funds and support from the government to improve a private market to operate more efficiently. The SCC, by definition, is the marginal benefit of carbon dioxide emission reduction. Therefore, the intervention budget equals the SCC times unit of carbon dioxide being removed by tree plantations.

The conservative estimate shows additional social net benefits from private tree plantations in monetary value equals $982/ha, on average, over 30 years. By using 1.2 million hectares of tree plantations allocated by the Government, this can be translated to additional social benefits of

$1,178 million over 30 years. With the first equimarginal principle, the Government should allocate $1,178 million over 30 years for improving existing infrastructure and regulations to raise the private rate of return efficiently. Eventually, the private sector can expand their plantations.

Converting this future benefit into a present term results in $394/ha or $472.8 million[14] over 30 years. This implies that under the conservative estimate, the budget required to improve the efficiency of tree plantations for the private sector in Lao PDR is $472.8 million in today's value, which is 2.3% of the gross domestic product in 2020[15].

The implication of this study to policymakers can be summarized as follows.

(1) Government intervention in the private tree plantations market is justified because the social rate of return is higher than the private rate of return. Though the private sector voluntarily engages in tree plantations, existing issues related to tree markets in Lao PDR are the barriers for the private sector to maximize their financial returns.

(2) The social rate of return is not sensitive to the economic value of carbon sequestration in private tree plantations, as the benefits of carbon sequestration are small compared to financial benefits from selling timber. In other words, assigning a higher social cost of carbon does not significantly affect an intervention priority. However, the selection of a social cost of carbon affects the budget intervention. Given limited data on damage due to climate change in the country, it is rational to assign a social cost of carbon at a lower bound.

(3) The intervention budget is estimated at $472.8 million in today's value for 30 years, which is 2.3% of the gross domestic product in 2020. The result of this study is based on the current land allocation for tree plantations by the Government.

(4) This budget can be used to improve the quality of timber, regulations, knowledge exchanges, market prices, and some other climate-related activities. A focus group discussion with relevant agencies for ranking activity priorities can help to allocate this budget.

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[14] $394/ha * 1.2 million ha = $472.8 million.

[15] The GDP in 2018 was reported at $17.87 billion with the growth rate of 6.29% per year (https://www.lsb.gov.la/en/home/), the GDP in 2020 is projected to be $20.26 billion.

To endorse the budget estimate in this study requires further considerations by carefully investigating several assumptions used in this study. The study assumptions are based on peer-reviewed journals, value judgments from prominent researchers in the field, and lessons learned from mainly developed countries. Some of those assumptions are politically debatable and subject to the country's effort and commitment to combat climate change. The effects of the study assumption are summarized in the following table, which shows a negative sign if the assumption results in a conservative estimate of benefits, and a positive sign where the assumption may not be as conservative; a question mark is used if the direction of the effect is unknown.

Table 5.1 The effects of the study assumption

No.	Affected component	Assumptions	Effect
1	Market value	Previous studies on financial returns done by Maraseni et al. (2018) and Phimmavong et al. (2019) did not explicitly indicate how expenses are distributed for some items. For example, overhead costs, including concession fees and community development funds, are not known if they are a one-off payment or recurring expense. We assume the overhead costs were a one-off payment paid at the beginning of the plantation year, which would drive down costs as compared to a recurring expense.	-
2	Market value	The land expectation value is widely used to measure a long-term value of bare land at the start of an even-aged forest rotation, mainly to identify optimal even-aged management aiming at maximizing financial returns. With the assumption of identical rotations, a change in costs of plantations and timber prices is not considered. The NPV results are expected to be either higher or lower, depending on which components have a higher change in magnitude.	?
3	Market value	The study uses the CPI inflation rate to adjust all costs and timber prices from different years to the real values in 2020. Since timber is known as a raw good, it is reasonable to use the inflation rate of the producer price index (PPI). However, due to unavailable data in the country, the CPI inflation rate is used.	?

Table 5.1 (continued)

No.	Affected component	Assumptions	Effect
4	Market value	To avoid the effect of the foreign exchange rate, the CBA would be conducted in the local currency. However, the existing data on costs of plantations and timber prices were reported in the US dollars with possible errors of round numbers. Thus, costs and prices, expressed in US dollars, are assumed not to be affected by the exchange rate. The exchange rate from LAK (Lao Kip) to USD is 8,297 ± 0.83% from 2016 to 2020[16], which is not highly fluctuated.	?
5	Market value	The value of tree plantations changes over time, mainly due to scarcity rent going up given lower quantities available. The real value of trees would also expect to be increasing. Unfortunately, there is no dataset on the price of trees to justify if scarcity rent exists in tree plantations in Lao PDR. The NPV results are expected to be higher when considering the increase in the real timber prices.	-
6	Market value	The effect of technological progress is assumed to be minimal for a short-term investment. Technological progress reduces the real growth rate of per capita consumption. In return, it reduces the social discount rate estimated by using Ramsey's formula. The NPV with consideration of technological progress will be higher.	-
7	Non-market value	The focus of this study is to quantify non-market benefits to the country populations. However, it does not change the fact that the rest of the world, which is a third party for this study, also gets benefits if the proposed government intervention take place in Lao PDR. There may be positive externalities that are unquantified within the scope of study.	-
8	Non-market value	Eucalyptus is known for environmental degradation, as it replaces indigenous forests, depleting food and shelter sources and therefore affecting animals and birds. Also, it degrades soil quality that becomes unsuitable for some other tree species, reducing the future possibility of biodiversity enhancement. The NPV results might be lower when considering this cost.	+

[16] The exchange rate was from https://www.lsb.gov.la/lsb-la.htm, and the descriptive statistics was done for data from 2016 to 2020.

Table 5.1 (continued)

No.	Affected component	Assumptions	Effect
9	Non-market value	CO_2 sequestration potential can be directly estimated by converting tree volumes to carbon storage and then to the CO_2 sequestration amount. However, due to data limitation of tree volumes or yields for Lao PDR, it is impossible to estimate using such a method. Therefore, the CO_2 sequestration was estimated from reported carbon storage from each tree species in equations. The regression analysis from existing literature was used, which might be subject to overfitting, sampling bias, and outliers.	?
10	Non-market value	It is intuitive to assign the value of $1/t$CO_2$ for the SCC following some countries who apply the SCC in carbon taxes at $1 - $5/t$CO_2$ regardless of the difference in terms of economic scale and energy mix. Nevertheless, the ex-ante SCC in this study is set at a lower bound.	-
11	Non-market value	The study considers only one type of non-market value, which is for CO_2 sequestration. There are many benefits of tree plantations. Therefore, the results underestimate the total economic value of tree plantations.	-
12	Non-market value	The assumption of SCC is to capture all damage caused by climate change within the country. However, it is challenging to justify when the SCC variable can take on a wide range. As such, a sensitivity analysis is performed.	?
13	Non-market value	The GHG re-emissions such as burning, if any, are not considered in this study. It is a separate issue that is not covered by tree plantation activity but would create losses.	+

The assumptions above affect either market or non-market values to estimate net benefits. The results of this study focus on non-market value as it is used as a basis to determine the intervention budget. Given the best available data and possible conservative assumptions, the study is still subject to uncertainty, where the effect of some assumptions cannot predict the direction. This can be enhanced through future research studies.

Upon the completion of this study, further consideration of negative externalities such as environmental impacts from tree plantations should be considered, such as environmental degradations (item 8 in Table 5.1). Also, revision of CO_2 sequestration function should be made when there is a study on a tree yield function so that the CO_2 sequestration can be estimated based on a yield function, not a regression from existing literature (item 9 in Table 5.1). The SCC should be estimated based on local economic damages due to climate change. This requires a well-established database to store historical disasters, and a damage assessment should be done to determine the magnitude of damage due to anthropogenic GHG emissions (item 12 in Table 5.1). Lastly, to minimize a possible carbon leakage (a reduction of GHG emissions results in an increase of GHG emissions in another place), holistic planning and management should be considered by involving all agencies subject to GHG emissions.

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Appendix

A.1 Technical report – Cost and benefit analysis

This is the technical description of the cost-benefit analysis for private tree plantations in Lao PDR. It is a supplement to the main report. Unless otherwise specified, all input data on monetary values are expressed in 2020 real values (see Table 3.1, Table A.1, and Table A.2 for input data). In this analysis, market value is the income from timber harvesting, while the non-market value is the benefits of carbon dioxide sequestration. The detailed analysis is summarized as follows:

- Costs of plantations from previous studies were from 2017 and 2018 for teak and eucalyptus plantations, respectively. All costs were adjusted with the consumer price index (CPI) inflation rate of 3.74% (see Table A.15 for CPI) to arrive at the real costs in 2020 (Table A.1 and Table A.2). For example, the nominal costs of planting and land for teak plantations are \$616.3/ha and \$35/ha in 2017. Thus, the real costs of planting in 2020 are \$727.1/ha.

$$\begin{aligned} Real\ cost_{2020} &= Nominal\ cost_{2017} *\ (1 + inflation\ rate)^{\Delta t} \\ &= (\$616.3 + \$35) *\ (1 + 3.74\%)^{2020-2017} \\ &= \$727.1 \end{aligned}$$

- Timber prices were reported in 2017 and 2016 for teak and eucalyptus, respectively. All prices were adjusted to 2020 dollars by using the same CPI inflation rate as the costs. For example, the nominal price of teak timber is \$84/m^3 in 2017. Thus, the real price of teak timber in 2020 is \$93.78/m^3.

$$\begin{aligned} Teak\ real\ price_{2020} &= Nominal\ price_{2017} *\ (1 + inflation\ rate)^{\Delta t} \\ &= \$84 *\ (1 + 3.74\%)^{2020-2017} \\ &= \$93.78 \end{aligned}$$

$$\begin{aligned} Eucalyptus\ real\ price_{2020} &= Nominal\ price_{2016} *\ (1 + inflation\ rate)^{\Delta t} \\ &= \$48 *\ (1 + 3.74\%)^{2020-2016} \\ &= \$55.59 \end{aligned}$$

- Revenues or incomes from timber harvesting were calculated by multiplying a mean annual increment (MAI) and a harvesting year with a timber price. For example, the MAI of teak is 12.2 m^3/ha/year at the age of 18 years, and the timber price is \$93.78/m^3. Therefore, the income from harvesting is \$20,594/ha for one rotation. The total income over 30 years was calculated from the summation of income from each rotation.

$$\begin{aligned} Teak\ income &= MAI * Age * price \\ &= 12.2 * 18 * \$93.78 \\ &= \$20{,}594 \end{aligned}$$

- The benefits of carbon dioxide (CO_2) sequestration were calculated by multiplying the carbon dioxide sequestration potential with the social cost of carbon (SCC). Detailed analysis of the CO_2 sequestration potential is in Appendix A.2. If the SCC was set at \$1/tCO_2, and the amount of carbon dioxide sequestrated from the atmosphere in one year was 11 tCO_2/ha, the benefits of CO_2 sequestration in monetary terms was \$11/ha. The total benefit of CO_2 sequestration is the accumulation of the annual benefits over the predefined period, 30 years (see a list of assumptions below).

- The dual discounting approach was used. The real interest rate of 8.26% was applied for the market component (costs and incomes), while the social discount rate (SDR) of 6.9% was for the non-market component, in this case, benefits of CO_2 sequestration. The calculation of the real interest rate and the SDR is in the following.

The real interest rate = nominal interest rate – inflation rate
= 12% - 3.74%
= 8.26%

The social discount rate = $\rho + e * g$ (based on Ramsey's equation in Section 2.4)
= 1.0% + 1.0 * 5.9%
= 6.9%

- The present values (PV) for market and non-market components were calculated separately using the real interest rate and the SDR, respectively. For each component, the summation of the PVs is the net present value (NPV). The total NPV is the summation of the NPV-market and the NPV-nonmarket (See Table A.3 and Table A.4).

- A sensitivity analysis was done to identify the impact of the SDR and the SCC on the NPV-nonmarket (see Table A.5 and Table A.6).

A list of assumptions for the CBA is shown below.

- The CBA for teak and eucalyptus plantations was performed for 30 years, based on Law on Land (2013).
- Even-age plantations were assumed for all rotations except the last rotation, which trees are at the end of the 30 years.
- A constant MAI of tree species was assumed.
- The real costs of plantations obtained from Maraseni et al. (2018) and Phimmavong et al. (2019) did not change over the 30 years.
- Scarcity rent was set to zero - no changes in real prices of timber over the 30-year concession period.
- The CPI inflation rate of 3.74% was assumed to be constant (see Table A.15).
- The analysis was assumed not to be influenced by the foreign exchange rate, labor productivity, or technological progress. Also, the real growth rate of per capita consumption was assumed to be constant (see Table A.15).

Table A.1 Data on the nominal costs of teak plantations in 2017 with the real costs in 2020 adjusted at the inflation rate of 3.74%

Year	Nominal costs, $/ha (in 2017)			Real costs, $/ha (in 2020)	
	Planting costs	Land costs	Registration costs	Planting and land costs	Registration costs
0	616	35	0	727.1	0
1	147	19	0	178.6	0
2	103	15	0	122.6	0
3	63	15	0	78.1	0
4	63	15	0	75.9	0
5	0	0	56.8	0	52.8

Source: adapted from Maraseni et al. (2018).

Table A.2. Data on the nominal costs of eucalyptus plantations in 2018 with the real costs in 2020 adjusted at the inflation rate of 3.74%

	Nominal costs, $/ha (in 2018)				Real costs, $/ha (in 2020)		
Year	Planting costs	Land costs	Overhead costs	Harvesting cost	Planting and land costs	Overhead cost	Harvesting cost
0	1,193	0	1,260	0	1,283.9	1,356.0	0
1	120	50	0	0	176.4	0	0
2	25	50	0	0	75.0	0	0
3	17	50	0	0	64.6	0	0
4	17	50	0	0	62.3	0	0
5	17	50	0	0	60.0	0	0
6	17	50	0	0	57.8	0	0
7	17	50	0	3,300	55.8	0	2,746.5

Source: adapted from Phimmavong et al. (2019).

Note: Converting nominal costs to real costs was done by using equation 5 in Table A.16.

Table A.3. The detailed CBA for teak plantations discounted at 8.3% for net income and 6.9% for the benefits of CO_2 sequestration

	Market component				Non-market component			Total		
Year	Total cost	Timber yield	Total income	Net income benefits	Accumulated CO_2 sequestration	Annual incremental CO_2 sequestration	Annual incremental benefit of CO_2 sequestration	Present value of net income discounting at 8.3%	Present value of CO_2 benefits discounting at 6.9%	Total present value
	($)	(m^3/ha)	($)	($)	(tCO_2/ha)	(tCO_2/ha)	($)	($)	($)	($)
0	727.1	0	0	-727.1	0	0	0	-727.1	0	-727.1
1	178.6	0	0	-178.6	11.0	11.0	11.0	-165.0	10.2	-154.8
2	122.6	0	0	-122.6	29.4	18.4	18.4	-104.6	16.1	-88.5
3	78.1	0	0	-78.1	52.3	22.9	22.9	-61.6	18.8	-42.8
4	75.9	0	0	-75.9	78.8	26.5	26.5	-55.2	20.3	-35.0
5	52.8	0	0	-52.8	108.2	29.4	29.4	-35.5	21.1	-14.4
6	0	0	0	0	140.2	32.0	32.0	0	21.5	21.5
7	0	0	0	0	174.6	34.4	34.4	0	21.6	21.6
8	0	0	0	0	211.2	36.5	36.5	0	21.4	21.4
9	0	0	0	0	249.7	38.5	38.5	0	21.1	21.1
10	0	0	0	0	290.1	40.4	40.4	0	20.7	20.7
11	0	0	0	0	332.2	42.1	42.1	0	20.2	20.2
12	0	0	0	0	376.0	43.8	43.8	0	19.7	19.7
13	0	0	0	0	421.3	45.3	45.3	0	19.0	19.0
14	0	0	0	0	468.2	46.8	46.8	0	18.4	18.4
15	0	0	0	0	516.4	48.3	48.3	0	17.7	17.7
16	0	0	0	0	566.1	49.7	49.7	0	17.1	17.1
17	0	0	0	0	617.1	51.0	51.0	0	16.4	16.4
18	0	219.6	20,594.5	20,594.5	669.4	52.3	52.3	4,935.4	15.7	4,951.2
19	727.1	0	0	-727.1	0	0	0	-161.0	0	-161.0
20	178.6	0	0	-178.6	11.0	11.0	11.0	-36.5	2.9	-33.6
21	122.6	0	0	-122.6	29.4	18.4	18.4	-23.2	4.5	-18.6
22	78.1	0	0	-78.1	52.3	22.9	22.9	-13.6	5.3	-8.3
23	75.9	0	0	-75.9	78.8	26.5	26.5	-12.2	5.7	-6.5
24	52.8	0	0	-52.8	108.2	29.4	29.4	-7.9	5.9	-1.9
25	0	0	0	0.0	140.2	32.0	32.0	0	6.0	6.0
26	0	0	0	0.0	174.6	34.4	34.4	0	6.1	6.1
27	0	0	0	0.0	211.2	36.5	36.5	0	6.0	6.0
28	0	0	0	0.0	249.7	38.5	38.5	0	5.9	5.9
29	0	0	0	0.0	290.1	40.4	40.4	0	5.8	5.8
30	0	134.2	12,585.5	12,585.5	332.2	42.1	42.1	1,163.7	5.7	1,169.4
Total	2,470.3	353.8	33,180.0	30,709.7	6,989.4	1,001.6	1,001.6	4,695.7	397.0	5,092.7

Table A.4. The detailed CBA for eucalyptus plantations discounted at 8.3% for net income and 6.9% for the benefits of CO_2 sequestration

	Market component				Non-market component			Total		
Year	Total cost	Timber yield	Total income	Net income benefits	Accumulated CO_2 sequestration	Annual incremental CO_2 sequestration	Annual incremental benefit of CO_2 sequestration	Present value of net income discounting at 8.3%	Present value of CO_2 benefits discounting at 6.9%	Total present value
	($)	(m^3/ha)	($)	($)	(tCO_2/ha)	(tCO_2/ha)	($)	($)	($)	($)
0	2,639.9	0.0	0.0	-2,639.9	0.0	0.0	0.0	-2,639.9	0.0	-2,639.9
1	176.4	0.0	0.0	-176.4	12.8	12.8	12.8	-162.9	12.0	-151.0
2	75.0	0.0	0.0	-75.0	37.1	24.3	24.3	-64.0	21.2	-42.7
3	64.6	0.0	0.0	-64.6	69.1	32.0	32.0	-50.9	26.2	-24.7
4	62.3	0.0	0.0	-62.3	107.5	38.4	38.4	-45.3	29.4	-15.9
5	60.0	0.0	0.0	-60.0	151.4	43.9	43.9	-40.4	31.5	-8.9
6	57.8	0.0	0.0	-57.8	200.3	48.9	48.9	-35.9	32.8	-3.1
7	2,802.3	200.2	11,129.9	8,327.6	253.8	53.5	53.5	4,778.0	33.5	4,811.5
8	1,337.7	0.0	0.0	-1,337.7	0.0	0.0	0.0	-709.0	0.0	-709.0
9	176.4	0.0	0.0	-176.4	12.8	12.8	12.8	-86.3	7.0	-79.3
10	75.0	0.0	0.0	-75.0	37.1	24.3	24.3	-33.9	12.5	-21.5
11	64.6	0.0	0.0	-64.6	69.1	32.0	32.0	-27.0	15.4	-11.6
12	62.3	0.0	0.0	-62.3	107.5	38.4	38.4	-24.0	17.2	-6.8
13	60.0	0.0	0.0	-60.0	151.4	43.9	43.9	-21.4	18.5	-2.9
14	57.8	0.0	0.0	-57.8	200.3	48.9	48.9	-19.0	19.2	0.2
15	2,802.3	200.2	11,129.9	8,327.6	253.8	53.5	53.5	2,532.2	19.7	2,551.9
16	1,337.7	0.0	0.0	-1,337.7	0.0	0.0	0.0	-375.7	0.0	-375.7
17	176.4	0.0	0.0	-176.4	12.8	12.8	12.8	-45.8	4.1	-41.6
18	75.0	0.0	0.0	-75.0	37.1	24.3	24.3	-18.0	7.3	-10.7
19	64.6	0.0	0.0	-64.6	69.1	32.0	32.0	-14.3	9.0	-5.3
20	62.3	0.0	0.0	-62.3	107.5	38.4	38.4	-12.7	10.1	-2.6
21	60.0	0.0	0.0	-60.0	151.4	43.9	43.9	-11.3	10.8	-0.5
22	57.8	0.0	0.0	-57.8	200.3	48.9	48.9	-10.1	11.3	1.2
23	2,802.3	200.2	11,129.9	8,327.6	253.8	53.5	53.5	1,342.0	11.5	1,353.5
24	1,337.7	0.0	0.0	-1,337.7	0.0	0.0	0.0	-199.1	0.0	-199.1
25	176.4	0.0	0.0	-176.4	12.8	12.8	12.8	-24.2	2.4	-21.8
26	75.0	0.0	0.0	-75.0	37.1	24.3	24.3	-9.5	4.3	-5.2
27	64.6	0.0	0.0	-64.6	69.1	32.0	32.0	-7.6	5.3	-2.3
28	62.3	0.0	0.0	-62.3	107.5	38.4	38.4	-6.7	5.9	-0.8
29	60.0	0.0	0.0	-60.0	151.4	43.9	43.9	-6.0	6.3	0.3
30	2,804.4	171.6	9,539.9	6,735.5	200.3	48.9	48.9	622.8	6.6	629.4
Total	19,790	772.2	42,929.5	23,138.9	3,073.7	961.8	961.8	4,573.9	391.0	4,965

Table A.5. Benefits of CO_2 sequestration per hectare for teak plantations discounted at 1.5%, 3.5%, and 6.9% of the social discount rate (SDR)

Year	The SCC at $1/t$CO_2$				The SCC at $5/t$CO_2$			
	Annual incremental CO_2 benefits at SCC of $1/t$CO_2$, $	Present value of CO_2 benefits discounting at 1.5%, $	Present value of CO_2 benefits discounting at 3.5%, $	Present value of CO_2 benefits discounting at 6.9%, $	Annual incremental CO_2 benefits at SCC of $5/t$CO_2$, $	Present value of CO_2 benefits discounting at 1.5%, $	Present value of CO_2 benefits discounting at 3.5%, $	Present value of CO_2 benefits discounting at 6.9%, $
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	11.0	10.8	10.6	10.2	54.8	54.0	52.9	51.2
2	18.4	17.9	17.2	16.1	92.1	89.4	86.0	80.6
3	22.9	21.9	20.7	18.8	114.6	109.6	103.4	93.8
4	26.5	24.9	23.1	20.3	132.3	124.6	115.3	101.3
5	29.4	27.3	24.8	21.1	147.1	136.6	123.9	105.4
6	32.0	29.3	26.1	21.5	160.2	146.5	130.3	107.4
7	34.4	31.0	27.0	21.6	171.9	154.9	135.1	107.8
8	36.5	32.4	27.7	21.4	182.7	162.2	138.7	107.1
9	38.5	33.7	28.3	21.1	192.6	168.5	141.3	105.7
10	40.4	34.8	28.6	20.7	201.9	174.0	143.1	103.6
11	42.1	35.8	28.9	20.2	210.6	178.8	144.3	101.1
12	43.8	36.6	29.0	19.7	218.9	183.1	144.9	98.3
13	45.3	37.4	29.0	19.0	226.7	186.8	145.0	95.2
14	46.8	38.0	28.9	18.4	234.2	190.2	144.7	92.0
15	48.3	38.6	28.8	17.7	241.4	193.1	144.1	88.7
16	49.7	39.1	28.6	17.1	248.3	195.7	143.2	85.4
17	51.0	39.6	28.4	16.4	255.0	198.0	142.1	82.0
18	52.3	40.0	28.1	15.7	261.4	200.0	140.7	78.7
19	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
20	11.0	8.1	5.5	2.9	54.8	40.7	27.5	14.4
21	18.4	13.5	8.9	4.5	92.1	67.4	44.7	22.7
22	22.9	16.5	10.8	5.3	114.6	82.6	53.8	26.4
23	26.5	18.8	12.0	5.7	132.3	93.9	60.0	28.5
24	29.4	20.6	12.9	5.9	147.1	102.9	64.4	29.7
25	32.0	22.1	13.6	6.0	160.2	110.4	67.8	30.2
26	34.4	23.4	14.1	6.1	171.9	116.8	70.3	30.3
27	36.5	24.4	14.4	6.0	182.7	122.2	72.2	30.2
28	38.5	25.4	14.7	5.9	192.6	127.0	73.5	29.7
29	40.4	26.2	14.9	5.8	201.9	131.1	74.4	29.2
30	42.1	27.0	15.0	5.7	210.6	134.8	75.0	28.5
Total	1,001.6	795.1	600.6	397.0	5,007.9	3,975.6	3,002.8	1,985.1

Table A.6. Benefits of CO_2 sequestration per hectare for eucalyptus plantations discounted at 1.5%, 3.5%, and 6.9% of the SDR

	The SCC at $1/tCO_2$				The SCC at $5/tCO_2$			
Year	Annual incremental CO_2 benefits at SCC of $1/tCO_2$, $	Present value of CO_2 benefits discounting at 1.5%, $	Present value of CO_2 benefits discounting at 3.5%, $	Present value of CO_2 benefits discounting at 6.9%, $	Annual incremental CO_2 benefits at SCC of $5/tCO_2$, $	Present value of CO_2 benefits discounting at 1.5%, $	Present value of CO_2 benefits discounting at 3.5%, $	Present value of CO_2 benefits discounting at 6.9%, $
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	12.8	12.6	12.3	12.0	63.9	62.9	61.7	59.8
2	24.3	23.6	22.7	21.2	121.4	117.8	113.3	106.2
3	32.0	30.6	28.9	26.2	160.1	153.1	144.4	131.1
4	38.4	36.2	33.4	29.4	191.9	180.8	167.2	147.0
5	43.9	40.8	37.0	31.5	219.7	203.9	184.9	157.3
6	48.9	44.7	39.8	32.8	244.7	223.7	199.0	163.9
7	53.5	48.2	42.1	33.5	267.6	241.1	210.3	167.7
8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	12.8	11.2	9.4	7.0	63.9	55.9	46.9	35.0
10	24.3	20.9	17.2	12.5	121.4	104.6	86.0	62.3
11	32.0	27.2	21.9	15.4	160.1	135.9	109.7	76.8
12	38.4	32.1	25.4	17.2	191.9	160.5	127.0	86.2
13	43.9	36.2	28.1	18.5	219.7	181.0	140.5	92.3
14	48.9	39.7	30.2	19.2	244.7	198.6	151.1	96.1
15	53.5	42.8	31.9	19.7	267.6	214.0	159.7	98.4
16	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
17	12.8	9.9	7.1	4.1	63.9	49.6	35.6	20.5
18	24.3	18.6	13.1	7.3	121.4	92.8	65.3	36.5
19	32.0	24.1	16.7	9.0	160.1	120.7	83.3	45.1
20	38.4	28.5	19.3	10.1	191.9	142.5	96.4	50.5
21	43.9	32.1	21.3	10.8	219.7	160.7	106.7	54.1
22	48.9	35.3	23.0	11.3	244.7	176.3	114.8	56.4
23	53.5	38.0	24.3	11.5	267.6	190.0	121.3	57.7
24	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
25	12.8	8.8	5.4	2.4	63.9	44.0	27.0	12.0
26	24.3	16.5	9.9	4.3	121.4	82.4	49.6	21.4
27	32.0	21.4	12.6	5.3	160.1	107.1	63.2	26.4
28	38.4	25.3	14.6	5.9	191.9	126.5	73.2	29.6
29	43.9	28.5	16.2	6.3	219.7	142.6	81.0	31.7
30	48.9	31.3	17.4	6.6	244.7	156.5	87.2	33.1
Total	961.8	765.2	581.3	391.0	4,809.1	3,825.8	2,906.6	1,955.2

A.2 Technical report – CO_2 sequestration regression analysis

Regression analysis for CO_2 sequestration of teak and eucalyptus plantations was performed using Stata software. Data for analysis consisted of the CO_2 sequestration and the stand age of trees. CO_2 sequestration is the dependent variable, while the stand age is the independent variable. The CO_2 sequestration (tCO_2/ha) for teak and eucalyptus was converted from carbon pool stock (tC/ha) by multiplying with a unit convertor of 44/12 Carbon pool stock were gathered from literature and summarized in tables below.

Table A.7. Carbon pool stock for teak plantations

No	Species	Age (years)	tC/ha	Country	Reference
1	*Tectona grandis*	1	2.9	Panama	(Derwisch et al., 2009)
2	*Tectona grandis*	10	70.27	India	(Reddy et al., 2014)
3	*Tectona grandis*	10	40.7	Panama	(Derwisch et al., 2009)
4	*Tectona grandis*	15	108.53	India	(Reddy et al., 2014)
5	*Tectona grandis*	18	57.36	India	(Banerjee & Prakasam, 2013)
6	*Tectona grandis*	20	330	India	(Reddy et al., 2014)
7	*Tectona grandis*	20	351	Panama	(Kraenzel et al., 2003)
8	*Tectona grandis*	20	191.1	Panama	(Derwisch et al., 2009)
9	*Tectona grandis*	47	135.99	India	(Banerjee & Prakasam, 2013)
10	*Tectona grandis*	50	181.3	India	(Sreejesh et al., 2013) with thinning

Table A.8. Carbon pool stock for eucalyptus plantations

No	Type	Age (years)	tC/ha	Country	Reference
1	*E. urophylla x E. grandis*	3	31.6	China	(Du et al., 2015)
2	*E. tereticornis*	3	11.9	India	(Rawat & Negi, 2004)
3	*Eucatypus ep*	3.6	27.7	Santa Maria	(Wink et al., 2013)
4	*E. tereticornis*	5	18.7	India	(Kushalapa, 1993)
5	*E. tereticornis*	6	28.2	India	(Kushalapa, 1993)
6	*E urophylla x E. grandis*	6 to 8	70.1	China	(Du et al., 2015)
7	*Eucalyptus tereticornis*	7	64	India	Sankaran (1999,2000) in (Yamada et al., 2004)
8	*Eucalyptus tereticornis*	9	146	India	(Rawat & Negi, 2004)
9	*Eucalyptus tereticornis*	10	108	India	(Prasad et al., 1998)
10	*Eucatypus occidentalis*	26	53.3	Australia	(Harper et al., 2012)

Two mathematical models were analyzed: the log-log model and the quadratic model (see Table A.9). These mathematical models are suitable for having a zero intercept, as trees do not sequestrate CO_2 when the stand age is zero.

Table A.9. Economic models for regression

Model	Economical model
Log-log model	$\ln CO_2seq = \mathrm{b}_0 + \mathrm{b}_1 \ln Age$
Quadratic model with a constraint suppressed to zero	$CO_2seq = \mathrm{b}_1 Age^2$

where CO_2seq is CO_2 sequestration (tCO_2/ha); $\ln CO_2seq$ is a natural log form of CO_2seq; Age is a stand age of tree (years); $\ln Age$ is a natural logarithm form of Age; b_0 is a constant coefficient, and b_1 and b_2 are the coefficients of the dependent variables. A zero constant is set for the quadratic model to represent zero growth at the stand age of zero. Meanwhile, the log-log model will result in the zero intersect after back-transformation. Smearing retransformation is used for the back-transformation of the log-log model (Duan, 1983). There are two retransformation equations, as shown in Table A.10. It is based on normality and homoscedasticity of the error term.

Table A.10. Smearing retransformation (Duan, 1983)

Condition for error term	Retransformation
Normally distributed and homoscedastic	$E(y\|x_0) = \exp(\mu)\exp\left(\frac{1}{2}\sigma^2\right)$
Not normally distributed but homoscedastic	$E(y\|x_0) = \exp(\mu)\,\mathrm{E}(\exp(\varepsilon))$

where $E(y|x_0)$ is expected value of y given x_0; μ is a mean value which is calculated from $\mathrm{b}_0 + \mathrm{b}_1 \ln x_0$; σ^2 is the variance of error or mean squared error (MSE), and ε is the error term. Note that the sample size for both teak and eucalyptus plantations is small, with eight observations for teak and ten for eucalyptus. However, there are enough degrees of freedom to estimate regression analysis with a high significance level.

A.2.1 Regression results for teak plantations

Results from regression analysis for CO_2 sequestration of teak plantations are shown in the table below. To evaluate if a regression is a good-fitting model, three metrics are widely used. The first metric is R-squared, which is a statistical measure of fit to indicate how well the regression is explained by the independent variable. It ranges from 0 to 1; 1 denotes 100% of regression is explained by the independent variable(s). The second is the f-test of overall significance, which represents the statistical significance of the overall relationship between dependent variable and independent variable(s). To interpret the value of the f-test, the probability value or p-value of statistical hypothesis testing is often used. When a p-value for the f-test is less than 0.05, it means that sample data provide sufficient evidence to conclude that a regression model fits the data with a 95% significance level. Lastly, RMSE is a measure of the closeness of a regression line to sample points. It is a suitable metric to compare different functional forms. Lower values of RMSE mean that the regression line is close to sample points, indicating a better-fit estimator.

For the significance of the individual coefficient, the Student's T-test or t-test is applied by looking at a p-value for the t-test from regression results. When a p-value for the t-test is less than 0.05, it indicates that the individual coefficient from the regression model is significant at a 95% significance level.

The regression results of the two models show very similar values in terms of p-values for the t-test and the f-test, and the R-squared, except the RMSE. P-values for the t-test for coefficients are less than 0.05. The R-squared is greater than 0.85, though it cannot be directly compared due to different functional forms of estimators. However, the RMSE for the quadratic model is much lower compared to the log-log model. Therefore, the log-log model is selected.

Table A.11. Summary of regression results for CO_2 sequestration for teak plantations

Model	**Coefficient**	**p-value for t-test**	**R-squared**	**p-value for F-test**	**RMSE**
$\ln CO_2seq = \mathrm{b}_0 + \mathrm{b}_1 \ln Age$	$b_0 = 2.2202$	0.008	0.87	0.0006	0.5892
	$b_1 = 1.4227$	0.001			
$CO_2seq = \mathrm{b}_1 Age^2$	$b_1 = 2.2535$	0.000	0.85	0.0004	286.16

The selected model was also checked for normality, heteroscedasticity, non-linearity, and model specification (see Table A.13 and section A.2.4 for the results of regression diagnostics). It shows that the selected model is an unbiased estimator. The error term, which is the difference between sample data and the predicted value, is normally distributed and homoscedastic. Therefore, retransformation was done as follows.

$$\ln CO_2seq = (2.2203 + 1.4228 \ * \ln Age)$$
$$CO_2seq = \exp(2.2203 + 1.4228 * \ln Age)\exp(0.5\ \sigma^2)$$
$$CO_2seq = \exp(2.2203 + 0.5 * 0.3473\ ) * \exp(1.4228 * \ln Age)$$
$$CO_2seq = 10.9567 * Age^{1.4228}$$

where $\sigma^2 = (RMSE)^2 = (0.5892)^2 = 0.3473$, CO_2seq is CO_2 sequestration (tCO_2/ha) and Age is stand age (years).

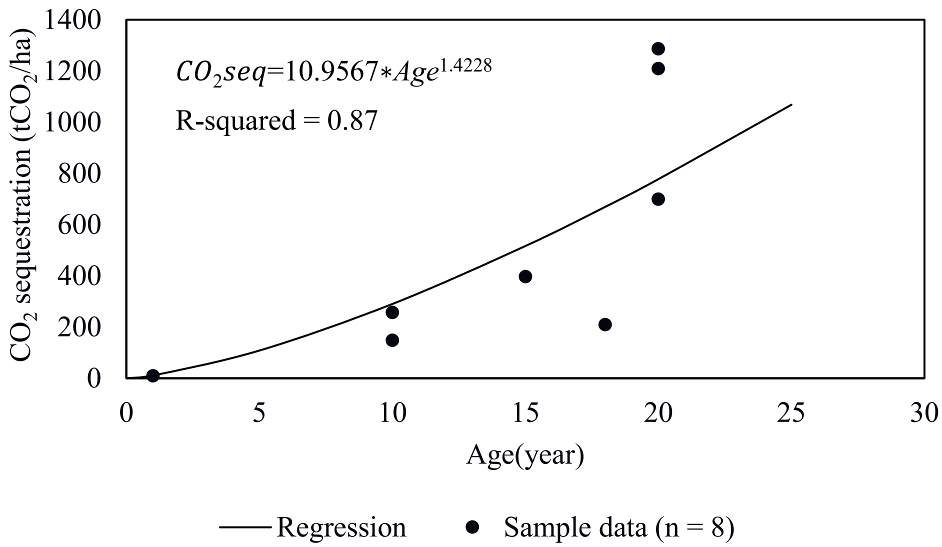


Figure A.1. CO_2 sequestration potential for teak plantations

A.2.2 Regression results for eucalyptus plantations

In the case of eucalyptus, it yields to the same model, which is the log-log model. The p-values for the t-test and the f-test are lower than 0.05 for both models, indicating statistically significant with a 95% confidence level. While the R-squared of the quadratic model is higher than that of the log-log model, however, the selection is more suitable on the basis of lower RMSE. The table below shows the regression results for eucalyptus plantations.

Table A.12. Summary of regression results for CO_2 sequestration for eucalyptus plantations

Model	Coefficient	p-value for t-test	R-squared	p-value for F-test	RMSE
$\ln CO_2seq = \mathrm{b}_0 + \mathrm{b}_1 \ln Age$	$b_0 = 2.4420$	0.004	0.70	0.0023	0.4594
	$b_1 = 1.5361$	0.002			
$CO_2seq = \mathrm{b}_1 Age^2$	$b_1 = 4.8243$	0.000	0.92	0.0000	76.315

The log-log model for eucalyptus is also an unbiased estimator based on tests for normality, heteroscedasticity, non-linearity, and model specification (see Table A.14 and section A.2.4 for the results of regression diagnostics). The error term is normally distributed and homoscedastic. Retransformation was done with the results as follows.

$$\ln CO_2seq = (2.4420 + 1.5361 \ * \ln Age)$$
$$CO_2seq = \exp(2.4420 + 1.5361 * \ln Age)\exp(0.5\ \sigma^2)$$
$$CO_2seq = \exp(2.4420 + 0.5 * 0.2110) * \exp(1.5361 * \ln Age)$$
$$CO_2seq = 12.7761 * Age^{1.5361}$$

where $\sigma^2 = (RMSE)^2 = (0.4594)^2 = 0.2110$, CO_2seq is CO_2 sequestration (tCO_2/ha) and Age is stand age (years).

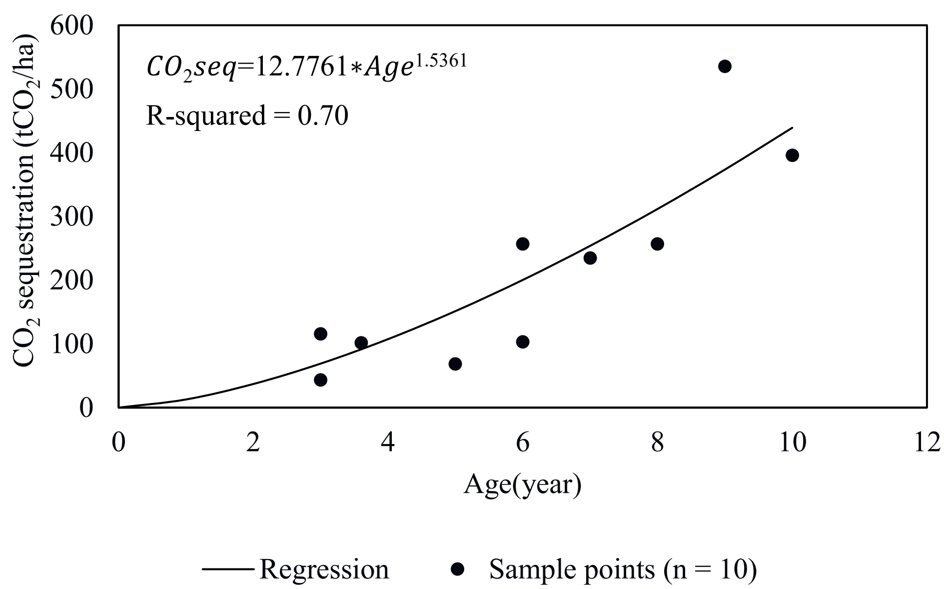


Figure A.2. CO_2 sequestration potential for eucalyptus plantations

A.2.3 STATA code for regression analysis

Using regression function in STATA, the results of regression analysis of CO_2 sequestration potentials were obtained. Given the S-shape yield curve of tree plantations, the non-linear form is expected for this regression. Further, omitting of outliers was done to improve the regression results. Regression diagnostic tests were done to ensure that the regression results are an unbiased estimator. The steps are summarized as follows. Graphical diagnostic results are in section A.2.4.

Procedure	Method and STATA command
Before running regression	
Summary statistics	Command: summarize *variable_names*
Check correlation	Method: Pearson's Correlation Command: corr *variable_names*
Tests for normality of data	Method: Shapiro-Wilk W test for normality Command: swilk *variable_names*
After running regression	
Tests for normality of residuals	Method: Shapiro-Wilk W test for normality Command swilk *residual*
	Method: Kernel density plot with normal distribution overlayed Command: kdensity *residual*, normal
	Method: Standardized normal probability (P-P) plot Command: pnorm *residual*
	Method: Plots the quantiles of variable_name against the quantiles of a normal distribution Command: qnorm *residual*
Tests for heteroscedasticity	Method: Cook and Weisberg test for heteroscedasticity. Command: estat imtest
	Method: White general test for Heteroscedasticity Command: estat hettest
Tests for multicollinearity	Method: Variance inflation factor Command: vif
Tests for non-linearity	Method: plot residual with independent variable Command: scatter *residual independent_variable*, yline(0)
	Method: Graphs an augmented component-plus-residual plot Command: acprplot *independent_variable*, lowess
	Method: Graphs component-plus-residual plot Command: cprplot *independent_variable*, lowess
Tests for model specification	Method: Link test for model specification Command: linktest
	Method: Ramsey's regression specification error test (RESET) for omitted variables Command: ovtest

Below box shows STATA codes and results of regression analysis.

Table A.13. Regression analysis using STATA for teak plantations

```
--------------------------------------------------------------------------------------
File: teak-regression.log
Analyst: Vongdalone Vongsikeo
Date: 3/11/2020
Variables: CO2seq as carbon dioxide sequestration potential (tCO2/ha) and Age as stand
age of tree (years)
--------------------------------------------------------------------------------------
================================ Function: log-log form ===============================
//summary statistics of data

. sum CO2seq Age

    Variable |        Obs        Mean    Std. Dev.       Min        Max
-------------+---------------------------------------------------------
      CO2seq |          8    527.9358    488.8885   10.63333       1287
         Age |          8       14.25    6.819091          1         20

//Check correlation coefficient. The results show a high correlation.

. corr CO2seq ln_CO2seq Age ln_Age
(obs=8)

             |   CO2seq ln_CO2~q      Age   ln_Age
-------------+------------------------------------
      CO2seq |   1.0000
   ln_CO2seq |   0.8179   1.0000
         Age |   0.7543   0.9249   1.0000
      ln_Age |   0.5974   0.9352   0.9304   1.0000

//perform Shapiro-Wilk W test to check the normality of data. "ln_" denotes natural log
//form. If Prob>z is less than 0.05, it means that the data is normally distributed at
//a 95% confidence level. The results show that Age and ln_Age have low p-values. Age
//and ln_Age is not normally distributed.

. swilk CO2seq ln_CO2seq Age ln_Age

                   Shapiro-Wilk W test for normal data

    Variable |        Obs       W           V         z       Prob>z
-------------+------------------------------------------------------
      CO2seq |          8    0.86298      1.909     1.133    0.12855
   ln_CO2seq |          8    0.86865      1.830     1.053    0.14620
         Age |          8    0.83104      2.354     1.548    0.06086
      ln_Age |          8    0.50765      6.859     4.210    0.00001

//log-log form: ln_CO2sseq = Coefficient0 + Coefficient1 * ln_Age.

. reg ln_CO2seq ln_Age

      Source |       SS           df       MS      Number of obs   =         8
-------------+----------------------------------   F(1, 6)         =     41.85
       Model |  14.5328467         1  14.5328467   Prob > F        =    0.0006
    Residual |  2.08358582         6  .347264303   R-squared       =    0.8746
-------------+----------------------------------   Adj R-squared   =    0.8537
       Total |  16.6164325         7  2.37377607   Root MSE        =    .58929

------------------------------------------------------------------------------
   ln_CO2seq |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
      ln_Age |   1.422797   .2199366     6.47   0.001      .884631    1.960962
       _cons |   2.220251   .5672426     3.91   0.008     .8322586    3.608244
------------------------------------------------------------------------------

//store residual and fitted values

. predict r_ln, residual
```

```
. predict y_ln
(option xb assumed; fitted values)

//Perform Shapiro-Wilk W test to check normality of residuals. If Prob>z is less than
//0.05, it means that the residuals are normally distributed at a 95% confidence level.
//The results show that high p-values. Therefore, the residuals are normally
//distributed.

. swilk r_ln

                   Shapiro-Wilk W test for normal data

    Variable |        Obs       W           V         z       Prob>z
-------------+------------------------------------------------------
        r_ln |          8    0.93608      0.890    -0.184    0.57296


//Kernel density plot with normal distribution overlayed.

. kdensity r_ln, normal
(n() set to 8)

//Standardized normal probability (P-P) plot.
//pnorm is sensitive to non-normality in the middle range of data.

. pnorm r_ln

//Plots the quantiles of variable_name against the quantiles of a normal distribution
//qnorm is sensitive to non-normality near the tails.

. qnorm r_ln

//perform Cook and Weisberg test for heteroscedasticity. The null hypothesis is the
//variance of the residuals is homogeneous. The null hypothesis is not rejected; the
//variance of the residuals is homogeneous.

. estat imtest

Cameron & Trivedi's decomposition of IM-test

---------------------------------------------------
              Source |       chi2     df      p
---------------------+-----------------------------
  Heteroskedasticity |       1.67      2    0.4340
            Skewness |       1.26      1    0.2613
            Kurtosis |       0.17      1    0.6786
---------------------+-----------------------------
               Total |       3.10      4    0.5407
---------------------------------------------------

//perform Breusch-Pagan / Cook-Weisberg test for heteroskedasticity
//The null hypothesis is that the variance of the residuals is homogeneous. Not reject
//the null hypothesis, the variance of the residuals is homogeneous.

. estat hettest

Breusch-Pagan / Cook-Weisberg test for heteroskedasticity
         Ho: Constant variance
         Variables: fitted values of ln_CO2seq

         chi2(1)      =     0.85
         Prob > chi2  =   0.3573

//vif to check for multicollinearity. There is only one independent variable, no
//multicollinearity. If VIF values are greater than 10, further investigation is
//required.

. vif
```

```
    Variable |       VIF       1/VIF
-------------+----------------------
      ln_Age |      1.00    1.000000
-------------+----------------------
    Mean VIF |      1.00

//scatter plot of the residuals and independent variables to test for non-linearity.

. scatter r_ln ln_Age, yline(0)

//perform an augmented component-plus-residual plot to test for non-linearity.

. acprplot ln_Age, lowess

//perform a component-plus-residual plot to test for non-linearity.

. cprplot ln_Age, lowess

//perform a link test for model specification.
//p-value is greater than 0.05. it means there is no specification error.

. linktest

      Source |       SS           df       MS      Number of obs   =         8
-------------+----------------------------------   F(2, 5)         =     21.08
       Model |  14.8547051         2  7.42735254   Prob > F        =    0.0037
    Residual |  1.76172743         5  .352345485   R-squared       =    0.8940
-------------+----------------------------------   Adj R-squared   =    0.8516
       Total |  16.6164325         7  2.37377607   Root MSE        =    .59359

------------------------------------------------------------------------------
   ln_CO2seq |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
        _hat |  -.2996942   1.368742    -0.22   0.835    -3.818159     3.21877
      _hatsq |   .1496255   .1565517     0.96   0.383    -.2528034    .5520545
       _cons |    2.30152   2.571415     0.90   0.412    -4.308513    8.911553
------------------------------------------------------------------------------

//perform a Ramsey RESET test for model specification and omitted variables.
//p-value is greater than 0.05; it means there is no specification error.

. ovtest

Ramsey RESET test using powers of the fitted values of ln_CO2seq
       Ho:  model has no omitted variables
                  F(3, 3) =      4.58
                  Prob > F =      0.1215

=============================== Function: Quadratic form ==============================

//regression with a constant suppressed to zero
//Age2 means Age to the power two, Age3 means Age to the power three

. regress CO2seq Age Age2 Age3, nocons

      Source |       SS           df       MS      Number of obs   =         8
-------------+----------------------------------   F(3, 5)         =     15.10
       Model |  3514840.97         3  1171613.66   Prob > F        =    0.0061
    Residual |  387972.537         5  77594.5073   R-squared       =    0.9006
-------------+----------------------------------   Adj R-squared   =    0.8409
       Total |   3902813.5         8  487851.688   Root MSE        =    278.56

------------------------------------------------------------------------------
      CO2seq |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
         Age |   167.3246   146.4873     1.14   0.305    -209.2329    543.8821
        Age2 |  -23.54513   20.04694    -1.17   0.293    -75.07742    27.98717
        Age3 |   .8854186   .6491603     1.36   0.231     -.783301    2.554138
------------------------------------------------------------------------------
```

```
. regress CO2seq Age2, nocons

      Source |       SS           df       MS      Number of obs   =         8
-------------+----------------------------------   F(1, 7)         =     40.66
       Model |  3329595.88         1  3329595.88   Prob > F        =    0.0004
    Residual |  573217.625         7  81888.2322   R-squared       =    0.8531
-------------+----------------------------------   Adj R-squared   =    0.8321
       Total |   3902813.5         8  487851.688   Root MSE        =    286.16

------------------------------------------------------------------------------
      CO2seq |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
        Age2 |   2.253594   .3534196     6.38   0.000     1.417889    3.089298
------------------------------------------------------------------------------

// F-test for the exclusion restriction.
// Null hypothesis is that the coefficient of Age and Age3 = 0
// sum of squared error for the restricted model, SSRr= 573217.625
// sum of squared error for the unrestricted model, SSRur = 387972.537
// number of restrictions, q = 2
// degrees of freedom in the unrestricted model, n - k - 1 = 5
// F-test = [(SSRr - SSRur)/q] / [SSRur/(n-k-1)]
//        = [(573217.625 - 387972.537)/2] / [387972.537/5]
//        = 1.67
// F-critical value, F-cr(0.05,2,5) = 5.78
// F-test < F-cr.
// Null hypothesis is not rejected. Therefore, Coeff-Age = Coeff-Age3 = 0

//to choose between log-log form and quadratic form, the Root MSE is very important.
//The smaller the root MSE, the better the estimator. The quadratic model has a much
//higher root MSE than that the log-log model. No further test is required.
```

Table A.14. Regression analysis using STATA for eucalyptus plantations

```
---------------------------------------------------------------------------------------
File: eucalyptus-regression.log
Analyst: Vongdalone Vongsikeo
Date: 3/11/2020
Variables: CO2seq as carbon dioxide sequestration potential (tCO2/ha) and Age as stand
age of tree (years)
---------------------------------------------------------------------------------------
================================ Function: log-log form ===============================

. sum CO2seq Age

    Variable |        Obs        Mean    Std. Dev.       Min        Max
-------------+---------------------------------------------------------
      CO2seq |         10      211.31     158.155   43.63333   535.3333
         Age |         10        6.06    2.465856          3         10

. corr CO2seq ln_CO2seq Age ln_Age
(obs=10)

             |   CO2seq ln_CO2~q      Age   ln_Age
-------------+------------------------------------
      CO2seq |   1.0000
   ln_CO2seq |   0.9445   1.0000
         Age |   0.8607   0.8645   1.0000
      ln_Age |   0.8112   0.8414   0.9852   1.0000

. swilk CO2seq ln_CO2seq Age ln_Age

                   Shapiro-Wilk W test for normal data

    Variable |        Obs       W           V         z       Prob>z
-------------+------------------------------------------------------
      CO2seq |         10    0.89073      1.684     0.943    0.17282
   ln_CO2seq |         10    0.96224      0.582    -0.882    0.81105
         Age |         10    0.94134      0.904    -0.171    0.56803
      ln_Age |         10    0.92137      1.212     0.336    0.36849

. reg ln_CO2seq ln_Age

      Source |       SS           df       MS      Number of obs   =        10
-------------+----------------------------------   F(1, 8)         =     19.39
       Model |  4.09401115         1  4.09401115   Prob > F        =    0.0023
    Residual |  1.68884928         8  .21110616    R-squared       =    0.7080
-------------+----------------------------------   Adj R-squared   =    0.6715
       Total |  5.78286043         9  .642540048   Root MSE        =    .45946

------------------------------------------------------------------------------
   ln_CO2seq |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
      ln_Age |    1.53615   .3488267     4.40   0.002     .7317547    2.340546
       _cons |    2.44202   .6171978     3.96   0.004      1.01876    3.865281
------------------------------------------------------------------------------

. predict r_ln, res

. predict y_ln
(option xb assumed; fitted values)

. swilk r_ln

                   Shapiro-Wilk W test for normal data

    Variable |        Obs       W           V         z       Prob>z
-------------+------------------------------------------------------
        r_ln |         10    0.96512      0.538    -1.004    0.84229
. kdensity r_ln, normal
(n() set to 10)
```

```
. pnorm r_ln

. qnorm r_ln

. estat imtest

Cameron & Trivedi's decomposition of IM-test

---------------------------------------------------
              Source |       chi2     df      p
---------------------+-----------------------------
  Heteroskedasticity |       2.02      2    0.3648
            Skewness |       0.43      1    0.5117
            Kurtosis |       0.92      1    0.3370
---------------------+-----------------------------
               Total |       3.37      4    0.4980
---------------------------------------------------

. estat hettest

Breusch-Pagan / Cook-Weisberg test for heteroskedasticity
         Ho: Constant variance
         Variables: fitted values of ln_CO2seq

         chi2(1)      =     0.64
         Prob > chi2  =   0.4226

. vif

    Variable |       VIF       1/VIF
-------------+----------------------
      ln_Age |      1.00    1.000000
-------------+----------------------
    Mean VIF |      1.00

. scatter r_ln ln_Age, yline(0)

. acprplot ln_Age, lowess

. cprplot ln_Age, lowess

. linktest

      Source |       SS           df       MS      Number of obs   =        10
-------------+----------------------------------   F(2, 7)         =     10.79
       Model |  4.36612837         2  2.18306418   Prob > F        =    0.0073
    Residual |  1.41673207         7  .202390295   R-squared       =    0.7550
-------------+----------------------------------   Adj R-squared   =    0.6850
       Total |  5.78286043         9  .642540048   Root MSE        =    .44988

------------------------------------------------------------------------------
   ln_CO2seq |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
        _hat |  -3.965688   4.288258    -0.92   0.386    -14.10581    6.174431
      _hatsq |   .4970044   .4286247     1.16   0.284    -.5165319    1.510541
       _cons |   12.19602   10.57956     1.15   0.287    -12.82066     37.2127
------------------------------------------------------------------------------

. ovtest

Ramsey RESET test using powers of the fitted values of ln_CO2seq
       Ho:  model has no omitted variables
                  F(3, 5) =      0.66
                 Prob > F =      0.6098

=============================== Function: Quadratic form ==============================

//regression with an assumption of zero constant
```

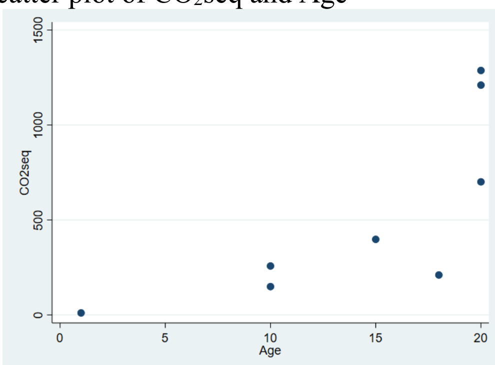
```
. reg CO2seq Age Age2 Age3, nocons

      Source |       SS           df       MS      Number of obs   =        10
-------------+----------------------------------   F(3, 7)         =     28.34
       Model |  620552.624         3  206850.875   Prob > F        =    0.0003
    Residual |  51083.5553         7  7297.65075   R-squared       =    0.9239
-------------+----------------------------------   Adj R-squared   =    0.8913
       Total |  671636.179        10  67163.6179   Root MSE        =    85.426

------------------------------------------------------------------------------
      CO2seq |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
         Age |   9.729099   47.05172     0.21   0.842    -101.5305    120.9887
        Age2 |   3.112656    13.8752     0.22   0.829    -29.69699     35.9223
        Age3 |   .0613065   .9724873     0.06   0.951     -2.23826    2.360873
------------------------------------------------------------------------------

. reg CO2seq Age2, nocons

      Source |       SS           df       MS      Number of obs   =        10
-------------+----------------------------------   F(1, 9)         =    106.32
       Model |  619220.253         1  619220.253   Prob > F        =    0.0000
    Residual |  52415.9258         9  5823.99175   R-squared       =    0.9220
-------------+----------------------------------   Adj R-squared   =    0.9133
       Total |  671636.179        10  67163.6179   Root MSE        =    76.315

------------------------------------------------------------------------------
      CO2seq |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
        Age2 |   4.824377   .4678742    10.31   0.000     3.765972    5.882782
------------------------------------------------------------------------------

// F-test for exclusion restriction.
// Null hypothesis is coefficient of Age and Age3 = 0
// sum of squared error for restricted model, SSRr= 52415.9258
// sum of squared error for unrestricted model, SSRur = 51083.5553
// number of restrictions, q = 2
// degrees of freedom in the unrestricted model, n - k - 1 = 7
// F-test = [(SSRr - SSRur)/q] / [SSRur/(n-k-1)]
//        = [(52415.9258 - 51083.5553)/2] / [51083.5553/7]
//        = 0.091
// F-critical value, F-cr(0.05,2,7) = 4.74
// F-test < F-cr.
// Null hypothesis is not rejected. Therefore, Coeff-Age = Coeff-Age3 = 0

//The quadratic model has a much higher root MSE than that of the log-log model.
//No further test is required.
```

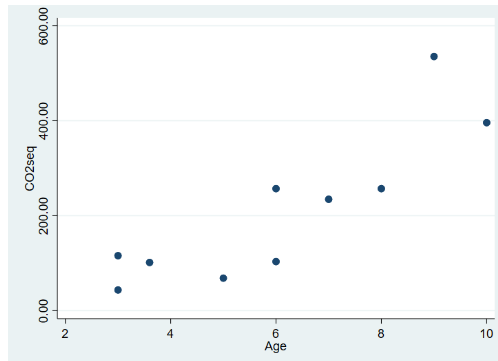
A.2.4 Regression diagnostics with graphs

Regression diagnostics with graphs for CO_2 sequestration of teak and eucalyptus plantations are shown here. The results show that overfitting is observed, particularly for data on teak. There is a minor non-linearity issue (see cprplot plots below). However, residuals are random with a normal distribution. It can be graphically concluded that the regression results are unbiased estimators.

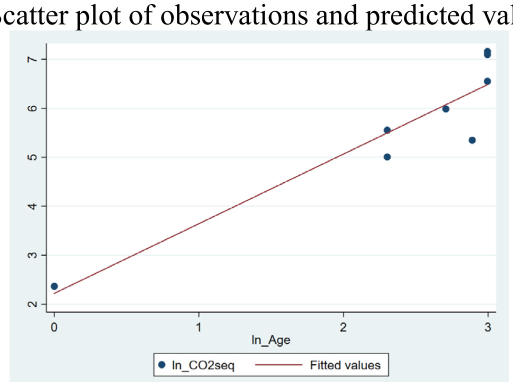
Teak	**Eucalyptus**

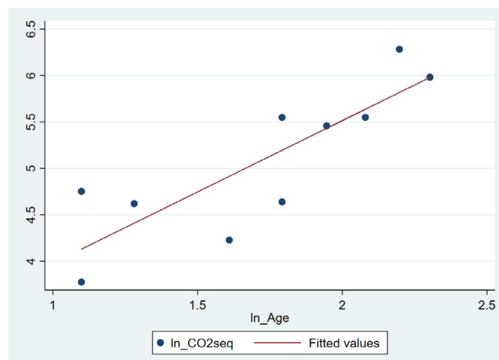
Scatter plot of CO_2seq and Age



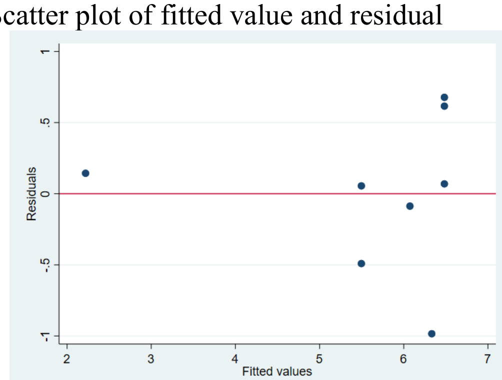


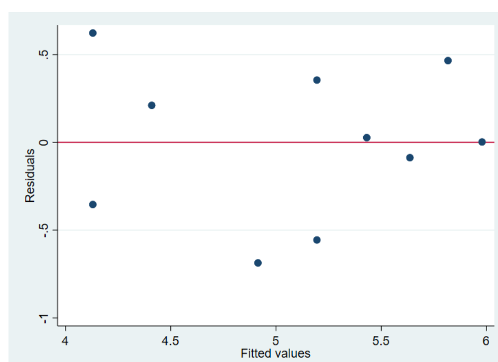
Scatter plot of observations and predicted value

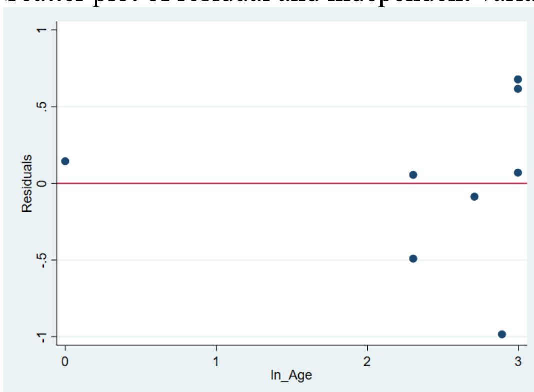
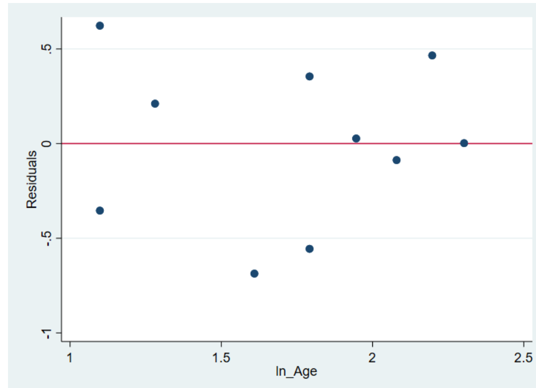
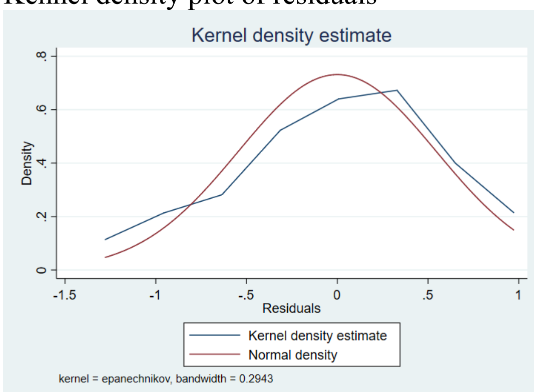
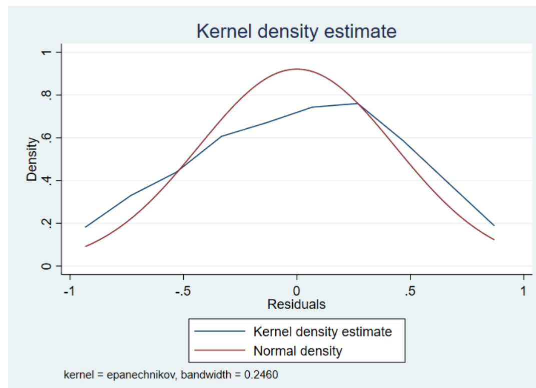
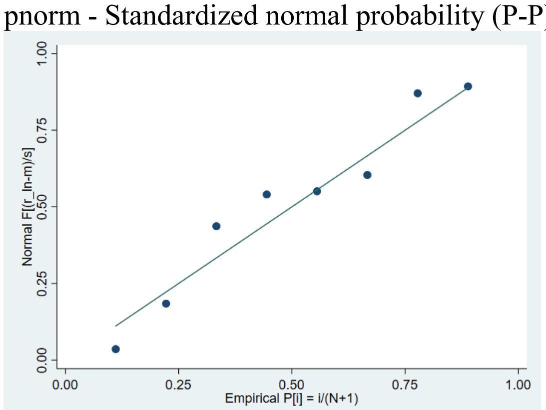
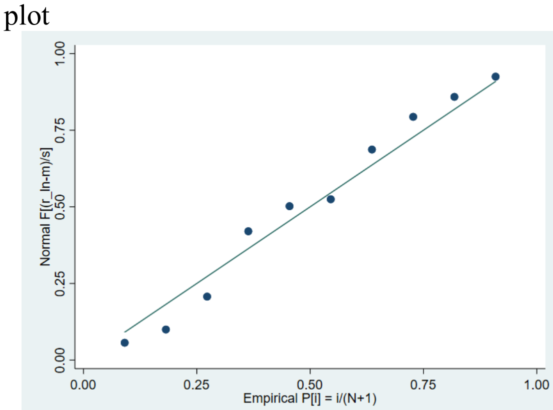




Scatter plot of fitted value and residual

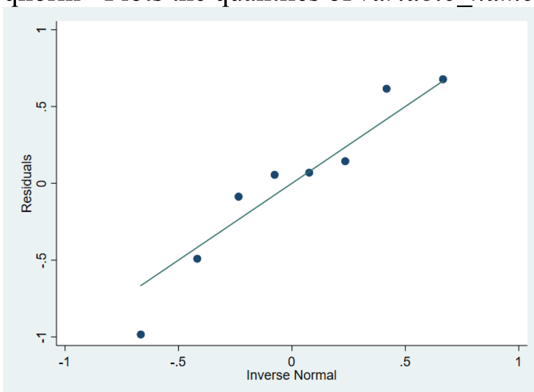


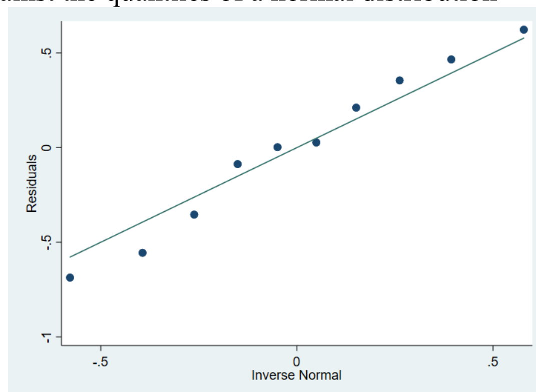


Teak	Eucalyptus
Scatter plot of residual and independent variable	
	
Kennel density plot of residuals	
	
pnorm - Standardized normal probability (P-P) plot	
	

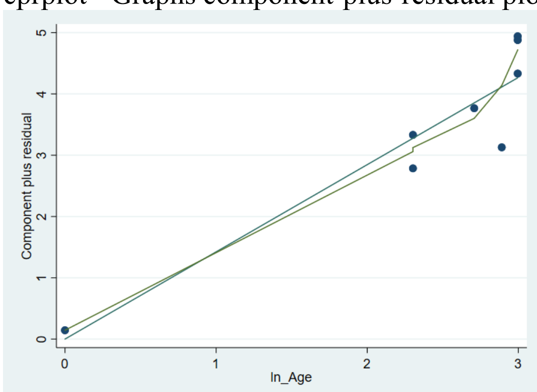
Teak	Eucalyptus

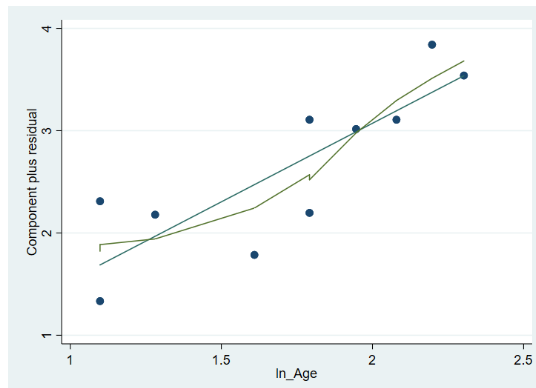
qnorm - Plots the quantiles of *variable_name* against the quantiles of a normal distribution





cprplot - Graphs component-plus-residual plot





A.3 Statistical data

Table A.15. Macroeconomic data

Year	Consumer price index (CPI)	Nominal GDP per cap (1,000 LAK)	Real GDP per cap (1,000 LAK)	CPI Inflation rate (%)	Real GDP per cap growth rate (%)
2009	74.78	7,724	8,186	-	-
2010	79.25	8,906	8,906	5.98	8.8
2011	85.26	10,141	9,426	7.58	5.8
2012	88.89	11,551	10,299	4.26	9.3
2013	94.55	12,733	10,672	6.37	3.6
2014	98.46	14,005	11,273	4.13	5.6
2015	99.71	18,060	14,354	1.28	27.3
2016	101.3	19,577	15,316	1.6	6.7
2017	102.14	20,354	15,792	0.83	3.1
2018	104.23	21,732	16,524	2.04	4.6
2019	107.69	-	-	3.32	-
Average				**3.74%**	**5.9%***

Source: Lao Statistics Bureau (2019) and BOL (n.d.) *excluded data in the year 2015; LAK means Lao Kip currency.

A.4 Formula sheet

<u>List of symbols</u>

NPV	Net present value (\$)
NFV	Net future value (\$)
PV	Present value (\$)
FV	Future value (\$)
R_t	Revenues at time *t* (\$)
C_t	Costs at time t (\$)
B_t	Benefits from CO_2 sequestration at time t (\$)
r	Real interest rate (%)
IRR	Internal rate of return (%)
SDR	Social discount rate (%)
Δt	difference in number of years (year)
t	Number of year (year)
T	Total time period (years)
CPI_t	Consumer price index at time t
$Nominal\ GDP\ cap_t$	Nominal GDP per capita at time t (local currency)
$Real\ GDP\ cap_t$	Real GDP per capita at time t (local currency)
B_t	Benefits at time t or benefits of CO_2 sequestration (\$)
C_t	Costs at time t (\$)
R_t	Revenues at time t (\$)
CF_t	Cash flow at time t (\$)
LEV	Land expectation value (\$)
MAI	Mean annual increment (m^3/ha/year)
Age	Stand age of tree (year)
$SRTP$	Social rate of time preference (%)
ρ	Pure time preference rate (%)
e	Elasticity of the marginal utility of consumption
g	Real GDP per capita growth rate (%)
CO_2seq	CO_2 sequestration potential (tCO_2/ha)
SCC	Social cost of carbon (\$/tCO_2)
α, β	Estimated parameter from regression analysis
$Yield$	Timber yield (m^3/ha)
$Price$	timber price (\$/m^3)

Table A.16. List of formula used in this study

No.	Parameter	Unit	Formula
1	CPI inflation rate	%	$\frac{CPI_t - CPI_{t-1}}{CPI_{t-1}}$
2	Real GDP per capita in a base year	Local currency	$Nominal\ GDP\ cap_t * \frac{CPI_{BASE}}{CPI_t}$
3	Real GDP per capita growth rate	%	$\frac{Real\ GDP\ cap_t - Real\ GDP\ cap_{t-1}}{Real\ GDP\ cap_{t-1}}$
4	Real interest rate	%	$Nominal\ interest\ rate - Inflation\ rate$
5	Value at time t_2	$	$Value_{t_1} * (1 + inflation\ rate)^{t_2 - t_1}$
6	Present value	$	$\frac{FV_t}{(1+r)^t}$
7	Net present value	$	$\sum_{t=0}^{T} \frac{B_t}{(1+r)^t} - \sum_{t=0}^{T} \frac{C_t}{(1+r)^t}$
8	New future value	$	$NPV * (1+r)^t$
9	Land expectation value	$	$\frac{NFV}{(1+r)^t - 1}$
10	Internal rate of returns	%	$\sum_{t=1}^{T} \frac{CF_t}{(1+IRR)^t} - CF_0 = 0$ Solve for *IRR*
11	Social rate of time preference (Ramsey's equation)	%	$SRTP = \rho + e * g$
12	Timber yield	m^3/ha	$MAI * Age$
13	Timber income	$	$Yield * Price$
14	CO_2 sequestration	tCO_2/ha	$\alpha * Age^{\beta}$
15	Benefits of CO_2 sequestration	$	$CO_2seq\ *\ SCC$

A.5 Supplements

Table A.17. Effects of rotation age on the total and the average CO_2 sequestration.

Rotation (years)	Concession year 0	1	2	3	4	5	7-26	27	28	29	30	Total, tCO_2/ha	Average, tCO_2/ha/year
Teak													
1	0	11	0	11	0	11	….	11	0	11	0	164	5.5
2	0	11	18.4	0	11	18.4	….	0	11	18.4	0	294	9.8
3	0	11	18.4	22.9	0	11	….	22.9	0	11	18.4	395	13.2
4	0	11	18.4	22.9	26.5	0	….	18.4	22.9	26.5	0	473	15.8
5	0	11	18.4	22.9	26.5	29.4	….	22.9	26.5	29.4	0	541	18.0
6	0	11	18.4	22.9	26.5	29.4	….	32	0	11	18.4	590	19.7
7	0	11	18.4	22.9	26.5	29.4	….	22.9	26.5	29.4	32	664	22.1
8	0	11	18.4	22.9	26.5	29.4	….	0	11	18.4	22.9	686	22.9
9	0	11	18.4	22.9	26.5	29.4	….	34.4	36.5	38.5	0	749	25.0
10	0	11	18.4	22.9	26.5	29.4	….	29.4	32	34.4	36.5	791	26.4
11	0	11	18.4	22.9	26.5	29.4	….	22.9	26.5	29.4	32	805	26.8
12	0	11	18.4	22.9	26.5	29.4	….	11	18.4	22.9	26.5	831	27.7
13	0	11	18.4	22.9	26.5	29.4	….	45.3	0	11	18.4	872	29.1
14	0	11	18.4	22.9	26.5	29.4	….	43.8	45.3	46.8	0	936	31.2
15	0	11	18.4	22.9	26.5	29.4	….	42.1	43.8	45.3	46.8	985	32.8
16	0	11	18.4	22.9	26.5	29.4	….	40.4	42.1	43.8	45.3	987	32.9
17	0	11	18.4	22.9	26.5	29.4	….	38.5	40.4	42.1	43.8	993	33.1
18	0	11	18.4	22.9	26.5	29.4	….	36.5	38.5	40.4	42.1	1002	33.4
19	0	11	18.4	22.9	26.5	29.4	….	34.4	36.5	38.5	40.4	1013	33.8
20	0	11	18.4	22.9	26.5	29.4	….	32	34.4	36.5	38.5	1027	34.2
Eucalyptus													
3	0	12.8	24.3	32	0	12.8	….	32	0	12.8	24.3	521	17.4
4	0	12.8	24.3	32	38.4	0	….	24.3	32	38.4	0	645	21.5
5	0	12.8	24.3	32	38.4	43.9	….	32	38.4	43.9	0	757	25.2
6	0	12.8	24.3	32	38.4	43.9	….	48.9	0	12.8	24.3	838	27.9
7	0	12.8	24.3	32	38.4	43.9	….	32	38.4	43.9	48.9	962	32.1
8	0	12.8	24.3	32	38.4	43.9	….	0	12.8	24.3	32	1004	33.5
9	0	12.8	24.3	32	38.4	43.9	….	53.5	57.8	61.8	0	1120	37.3
10	0	12.8	24.3	32	38.4	43.9	….	43.9	48.9	53.5	57.8	1190	39.7

By using CO_2 sequestration presented in section 0, CO_2 sequestration potentials for a range of stand age are obtained. The table above represents the change of CO_2 sequestration potentials for each year using $\Delta CO_2seq = CO_2seq_{current\ year} - CO_2seq_{previous\ year}$.

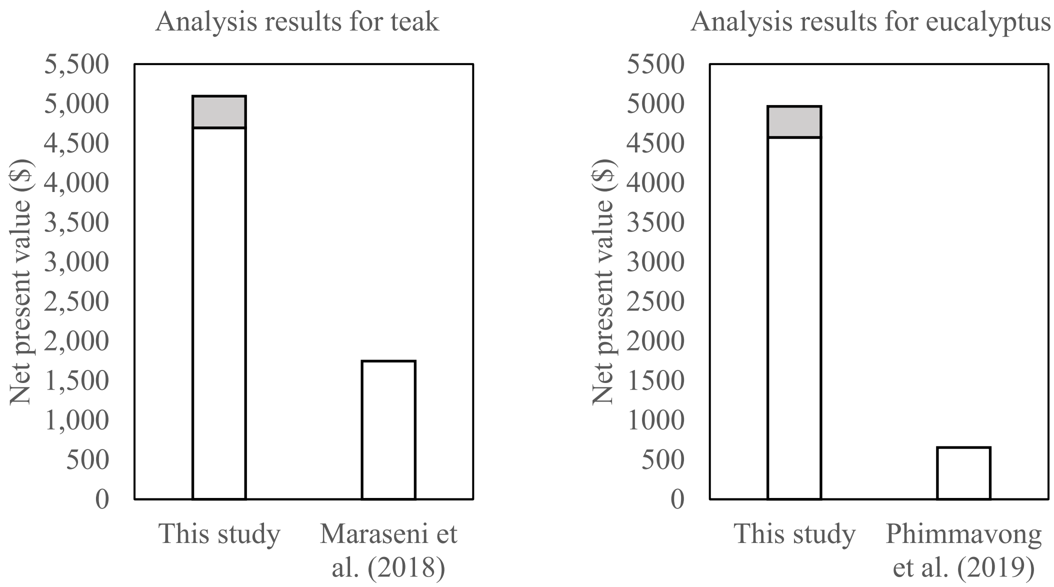


Figure A.3. Comparisons between this study and previous studies. Gray box denotes the benefits of non-market value for tree plantations. Net present values are reported in 2020.

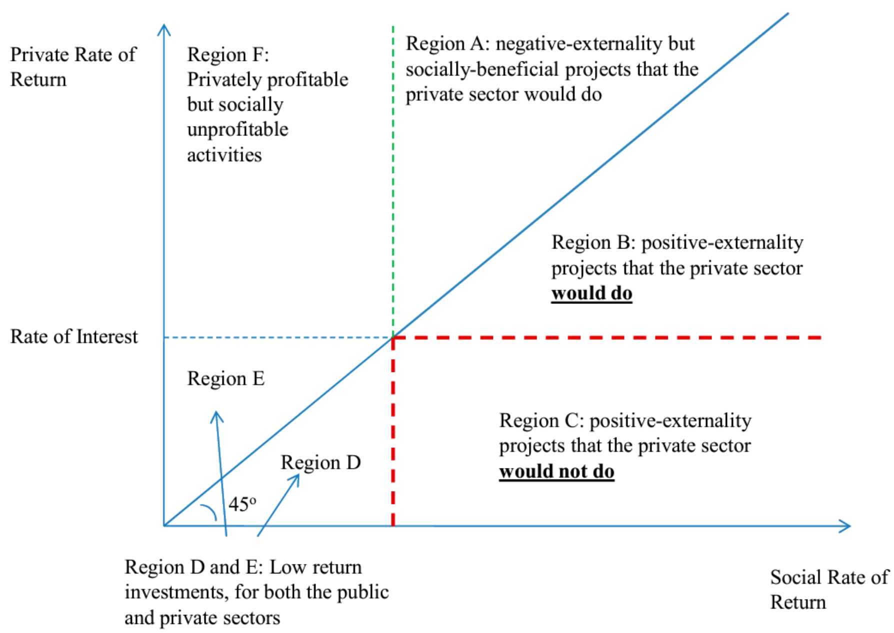


Figure A.4. State investments decision rules (Warner, 2013)

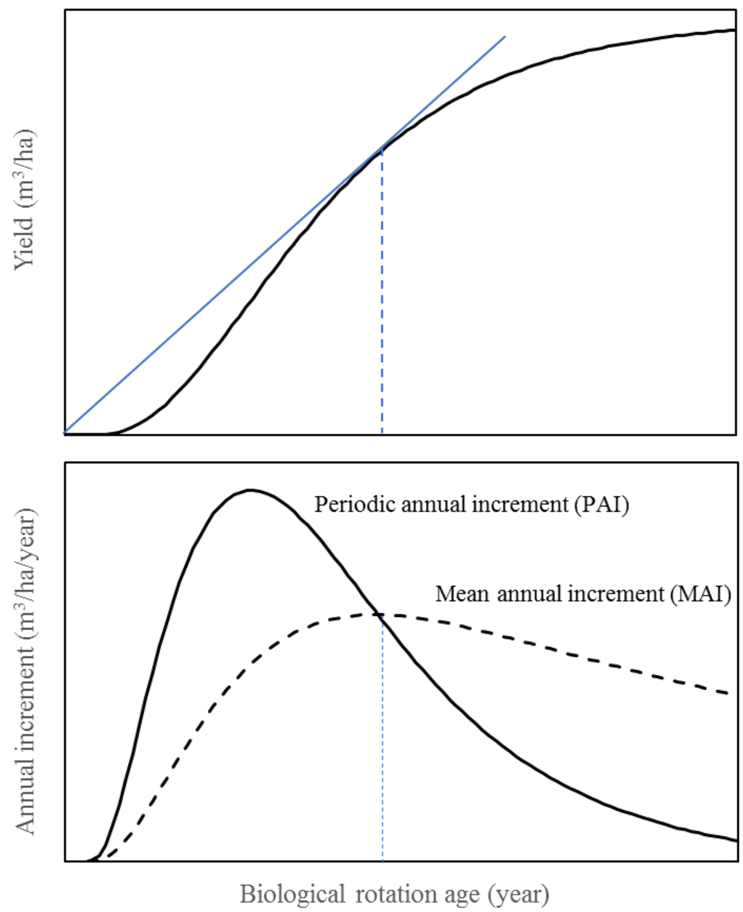


Figure A.5. Relationship of yield, mean annual increment, and biological rotation age

Table A.18. Non-market net present values (NPV) in 2020 dollars for different social cost of carbon (SCC) and social discount rate (SDR)

Plantations	SCC	SDR		
		1.5%	3.5%	6.9%
Teak	$1/t$CO_2$	$795	$601	$397
	$5/t$CO_2$	$3,976	$3,003	$1,985
Eucalyptus	$1/t$CO_2$	$765	$581	$391
	$5/t$CO_2$	$3,826	$2,907	$1,955
Average	$1/t$CO_2$	$780	$591	$394
	$5/t$CO_2$	$3,901	$2,955	$1,970